CONDUCTOR AND CONDUCTOR INSULATION

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Technology School on Superconducting Magnets
Snowmass, CO
18 July 2001

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Superconducting Materials

- There are three main types of commercially available superconducting materials *(see dedicated Technology Lecture)*
  - Niobium-Titanium Alloy (NbTi)
  - Niobium-Tin Compound (Nb_3Sn)
  - High Temperature Superconductors (HTS)

NbTi Alloys (1/4)

- The most widely used superconductor is a ductile alloy of niobium and titanium (NbTi).
- Niobium and titanium have very similar atomic sizes and are mutually soluble over a wide composition range.
- At high temperatures, they combine into a body-centered cubic phase, referred to as *β–phase*, which, when cooled down to temperatures below about 10 K, becomes a type-II superconductor.

NbTi Alloys (2/4)

- Furthermore, when the NbTi alloy is severely cold-worked and presents a large number of lattice dislocations, heat treatments at moderate temperatures lead to precipitations of other phases at grain boundaries.
- Among them is an hexagonal-close-packed phase, rich in titanium (of the order of 95% in weight), referred to as *α–phase*.
- The α–phase remains normal resistive at low temperatures and has been shown to be a significant source of fluxoid pinning sites.

NbTi Alloys (3/4)

- The critical temperature, T_C, and the upper critical magnetic flux density, B_{C2}, of niobium-titanium are mainly determined by alloy composition and are little affected by subsequent processing.
- The Ti-content of practical conductors is in the range 45 to 50% in weight and corresponds to an optimum in B_{C2}.
- For such compositions, the critical temperature at 0 T, T_{C0}, is between 9 and 9.2 K and the upper critical magnetic flux density at 0 K, B_{C20}, is about 14.5 T.

NbTi Alloys (4/4)

- The critical current density, J_C, is mainly determined by alloy microstructure and by the distribution and size of α–Ti precipitates.
- The α–Ti precipitates can be engineered to match the parameters of the fluxoid lattice at a given temperature and field and achieve optimum pinning.
- High performance wires have a typical J_C of 3000 A/mm^2 at 4.2 K and 5 T.

Ternary NbTi Alloys

- The upper critical magnetic flux density of NbTi alloys can be raised slightly by addition of a high-atomic-number ternary component such as tantalum.
- The increase in B_{C2} is 0.1 to 0.2 T at 4.2 K, but can reach 1 T at 2 K.
- However, more work is needed to optimize the critical current density of ternary alloys and reach the level achieved on binary alloys.
- So far, ternary NbTi alloys have had little practical applications.

On the Use of NbTi

- NbTi has good mechanical properties, and does not require special manufacturing processes.
- Given its superconducting properties, it is well suited for the production of fields in the 2-to-10-T range and requires cooling below 5-to-6-K (liquid helium).

Example: LHC arc dipole magnets (8.4 T at 1.9 K).

Nb_3Sn Compounds (1/4)

- The only other superconducting material that is readily available at (small) industrial scale is an intermetallic compound of niobium and tin, of formula Nb_3Sn, which belongs to the A15 crystallographic family.
- In intermetallic compounds, the valence electrons are not free to move as in metals, but are shared between neighboring strands to form covalent bonds.
- The covalent bonds enhance hardness, but renders Nb_3Sn very brittle and strain-sensitive.

Nb_3Sn Compounds (2/4)

- The stoichiometry of the A15 phase of Nb and Sn can very in the range 18.5 to 25 at% Sn.
- The critical temperature and the upper critical magnetic flux density exhibits a quasi-linear dependence on tin content, until about 23-to-24 at% Sn, where T_C levels off and B_{C2} goes through a maximum and starts to drop.
- This change in behavior is attributed to the existence of low-temperature martensitic phase transformation in compounds with a tin content in excess of 24.5 at%.

Nb_3Sn Compounds (3/4)

- The martensitic phase transformation can be eliminated by a small addition of Ti (typically: 1-to-2 wt%) or Ta (typically: 7.5 wt%)
- This elimination results in a B_{C2} enhancement.
- Most practical applications rely on ternary Nb_3Sn compounds, with a critical temperature at zero magnetic flux density and zero strain, T_{Com}, of about 18 K, and an upper critical magnetic flux density at zero temperature and zero strain, B_{C20m}, of about 28 T.

Nb_3Sn Compounds (4/4)

- The main source of fluxoid pining sites in Nb_3Sn has been shown to be grain boudaries.
- Hence, the microstructure must be engineered to achieve fine and homogenous grains.
- In recent years, several manufacturers around the world have developed high-performance Nb_3Sn wires with J_C in the 2000-to-2500-A/mm^2 range at 4.2 K and 12 T (*e.g.*, IGC and OST in the USA, and SMI in the Netherlands).

On the Use of Nb_3Sn

- Given its lousy mechanical properties and strain-sensitivity, Nb_3Sn is more difficult to use than NbTi and requires special manufacturing processes.
- It is well suited for the production of fields in the 10-to-21-T range and requires cooling below 10 to 15 K (liquid helium).

Example: high-field option for VLHC (12 T at 4.2 K?).

High Temperature Superconductors (1/3)

- In 1986, J.G. Berdnoz and K.A. Müller, two Swiss researchers working at IBM, discovered superconductivity in a copper oxide ceramics of composition $La_{2-x}Ba_xCuO_4$ (LBCO), with a critical temperature greater than 30 K when $x = 0.15$.

- LBCO was the first of what became known as the High Temperature Superconductors (HTS), and earned Berdnoz and Müller the Nobel prize in physics in 1987.

High Temperature Superconductors (2/3)

- At present, the most promising HTS are
  - $Bi_2Sr_2CaCu_2O_{8+x}$, referred to as BSCCO 2212, with a maximum T_C of 85 K,
  - $Bi_2Sr_2Ca_2Cu_3O_{10+x}$, referred to as BSCCO 2223, with a maximum T_C of 110 K,
  - $YBa_2Cu_3O_{6+x}$, referred to as YBCO 123, with a maximum T_C of 93 K.
- The record holder in terms of critical temperature is $HgBa_2Ca_2Cu_3O_{8+x}$, with 133 K at atmospheric pressure and 164 K under 30 GPa.

High Temperature Superconductors (3/3)

• In addition to their high critical temperatures, HTS materials also have high critical fields (tens of Teslas), especially at low temperatures (4.2 K).

• Over the last decade, there has been a steady increase in the quality of commercially available products, but the reliability and cost-efficiency of manufacturing processes and the overall transport-current properties of HTS are still too low.

On the Use of HTS (1/2)

- HTS materials are already used for current leads.

Example: 5-kA current leads implemented in a couple of Tevatron spool pieces at Fermilab.

On the Use of HTS (2/2)

- In the future, two main types of applications can be envisioned

  – high-temperature (77 K), low-field

  To benefit from high T_C, and replace expensive helium cooling (US$ 2.50/liter) by cheaper nitrogen cooling (US$ 0.06/liter)

  Example: low-field option for VLHC (2 T at 77 K?)

  – low-temperature (≤ 4.2 K), high-field

  To benefit from high B_{C2} and high transport-current properties at low temperature

Production and Costs of Superconductors

- NbTi

  ~2000 tons/year (round wires)
  ~US$ 150/kg (~US$ 1 kA/m)

- Nb_3Sn

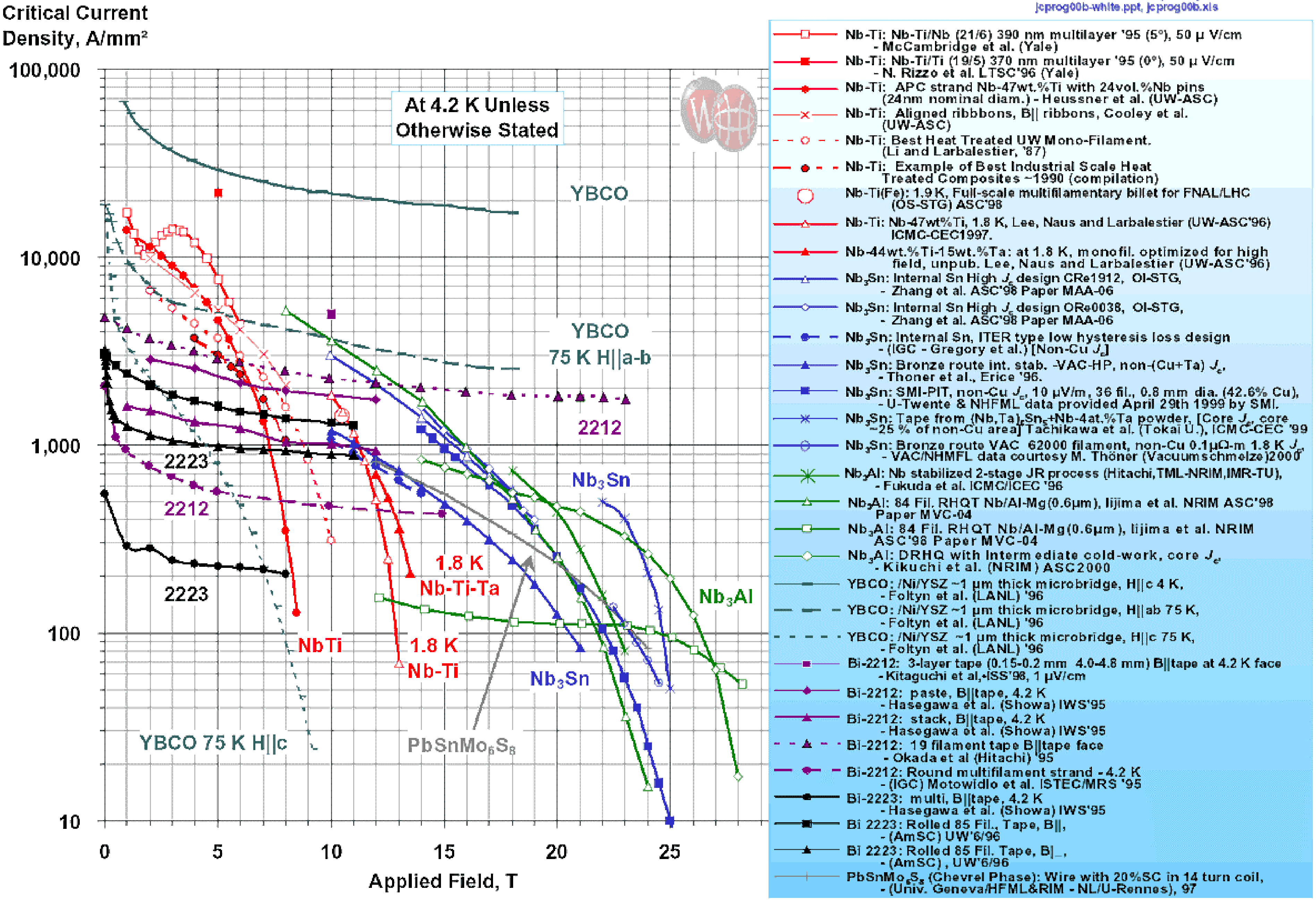
  ~15 tons/year (round wires)
  between US$ 750/kg and US$ 2000/kg
  (~US$ 5 kA/m)

- BSCCO + YBCO

  ~as much as 15 tons/year? (mostly tapes)
  ≥ US$ 5000/kg (~US$ 50 kA/m)

Advancing Critical Currents in Superconductors

University of Wisconsin-Madison
Applied Superconductivity Center
October 5th 2000 - Compiled by Peter J. Lee
jcprog00b-white.ppt, jcprog00b.xls



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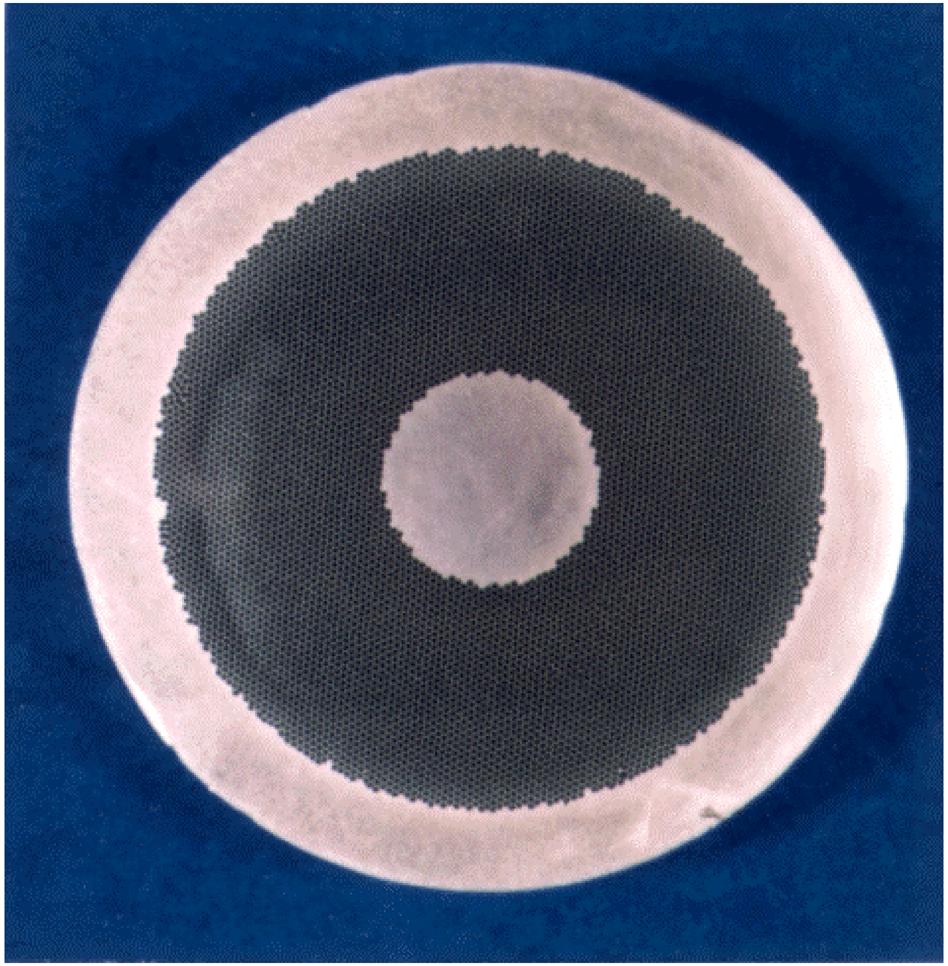
Multifilamentary Composite Wires (1/2)

- For practical applications, the superconductor is subdivided into fine filaments, which are twisted together and embedded in a low-resistivity matrix of normal metal (typically: pure OFHC copper).
- The subdivision into fine filaments is required to eliminate instabilities in the superconductor known as *flux jumps.*

Multifilamentary Composite Wires (2/2)

- The filament twisting is introduced to reduce inter-filament coupling when the wire is subjected to time-varying fields.
- The low-resistivity matrix is used as a current shunt in the case of a transition of the filaments to the normal resistive state, thereby limiting power dissipation and conductor heating (the resistivity of superconductors in the normal state is usually quite high).

Example: NbTi Wire for LHC



- Diameter: 1.065 mm
- Cu/Sc ratio: between 1.6 & 1.7
- Filament diameter: ~7 μm
- Number of Filaments: ~8900
- J_c (4.2 K, 7 T): 1550-1600 A/mm²

- LHC will require about 475 t of this wire.

(Courtesy Alsom/MSA)

Manufacturing of NbTi Wires

- NbTi alloy is very ductile and has very low work-hardening coefficients making it easy to co-process with copper.
- A NbTi multifilamentary wire is fabricated in three main steps:
  - production of NbTi alloy ingot.
  - production, extrusion and drawing of *mono-filament billet.*
  - production, extrusion and drawing of *multi-filament billet*.

Production of NbTi Ingot

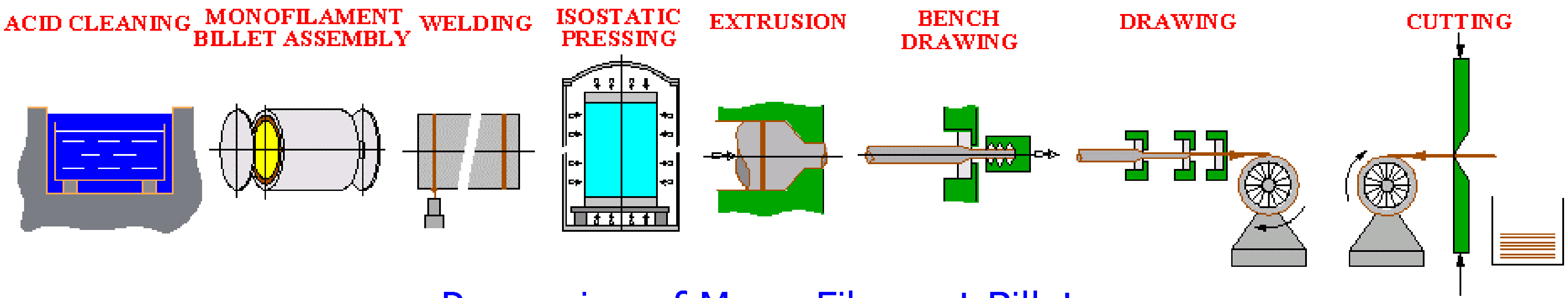
- The NbTi alloy is produced by consumable arc vacuum melting.
- Typical ingot parameters are:

Diameter	8'' (20.3 cm)
Height	30'' (76.2 cm)
Weigh	300 lbs (136.1 kg).

(Courtesy Oremet Wah Chang)

Mono-Filament Billet

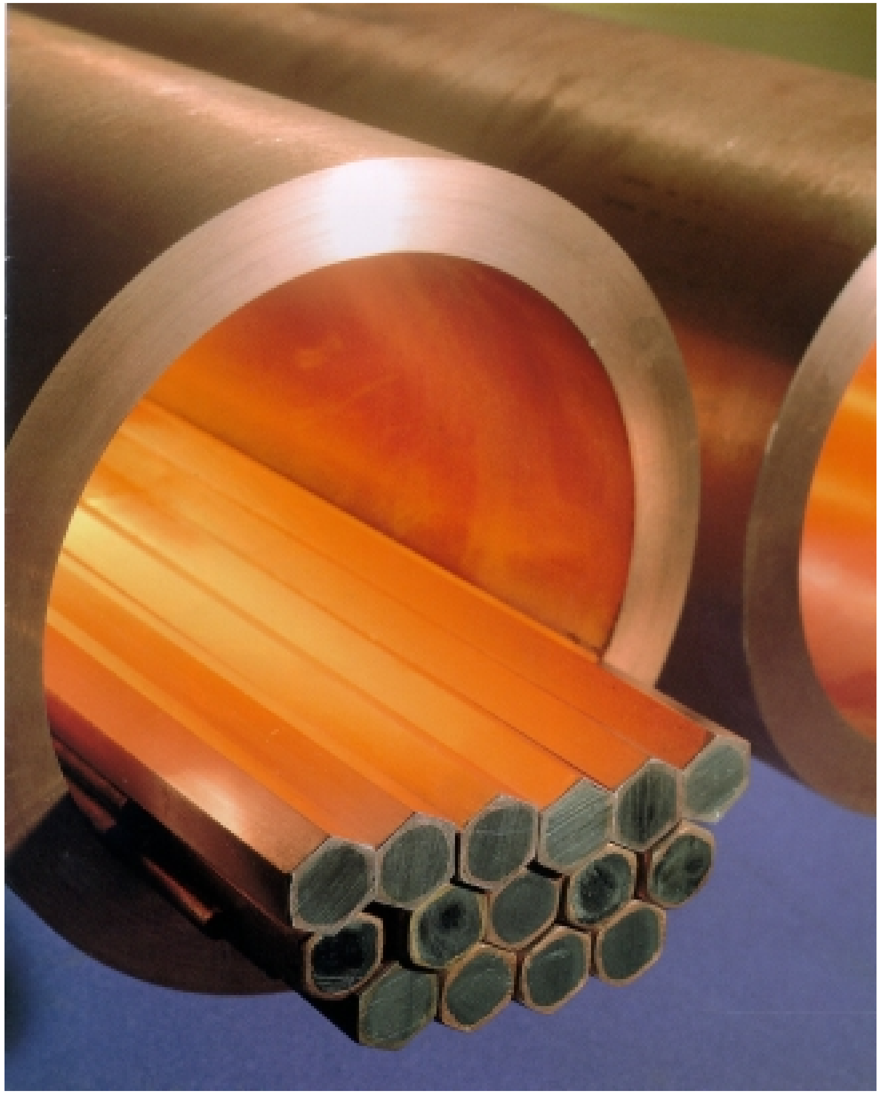
- The mono-filament billet is made up of a NbTi ingot inserted into a copper can.



Processing of Mono-Filament Billet
(Courtesy ALSTOM/MSA)

- The billet is extruded and drawn-down in several passes.
- At the last dawing pass, the mono-filament rod (which can be given an hexagonal shape) is cut into small pieces.

Multi-Filament Billet (1/2)

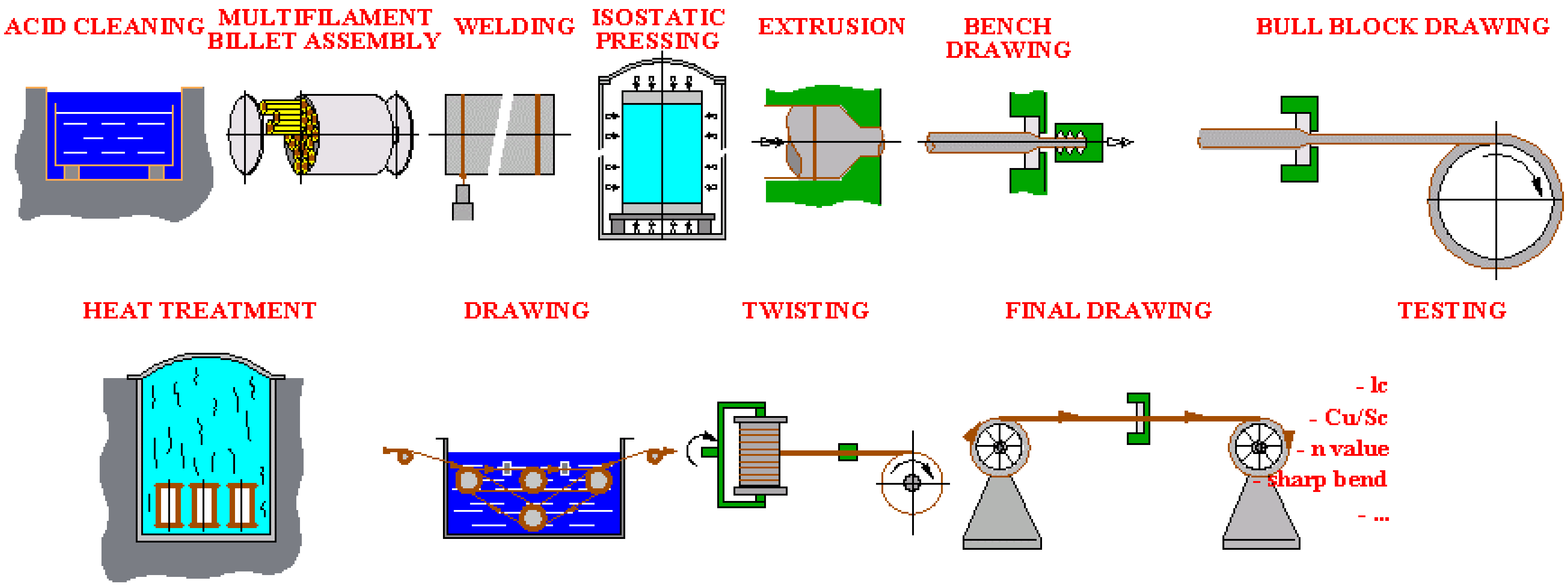


- The multi-filament billet is made up of mono-filament rods stacked into a thick-walled copper can.

(Courtesy Furukawa Electric Co.)

Multi-Filament Billet (2/2)

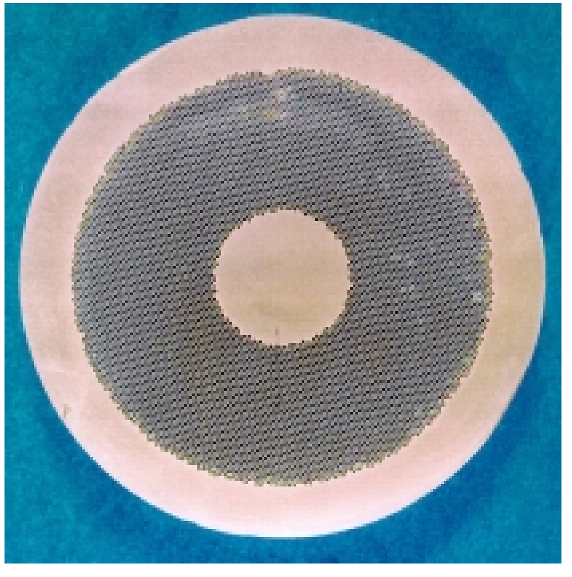
- The multi-filament billet is also extruded and drawn-down in several passes.



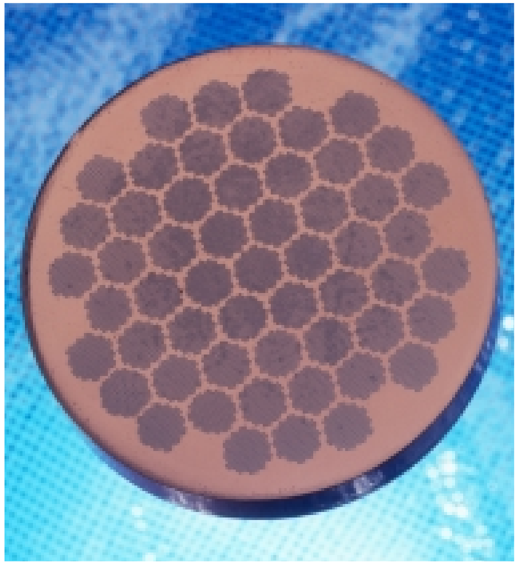
- The drawing passes are interleaved with heat-treatments at moderate temperatures, and the wire twist is applied prior to the final pass.

Multiple Stacking

- When the number of filaments is very large, rods made from a drawn-down multi-filament billet can be re-stacked into a new multi-filament billet, which, in turn, is extruded and drawn.
- Such process is referred-to as *double-stacking* as opposed to *single-stacking*.



Single-Stacking wire
(Courtesy Alstom/MSA)



Double-Stacking wire
(Courtesy Europa Metalli)

Manufacturing of Nb_3Sn Wires (1/4)

- Because of its brittleness, Nb_3Sn cannot be extruded and drawn as NbTi.
- The alternative is to proceed as follows
  - – assembly of a billet including un-compounded precursors of Nb_3Sn,
  - – processing of billet until achievement of desired wire size,
  - – cabling and/or winding (when needed),
  - – treatment of final wire (or cable or coil) to form Nb_3Sn compound.

Manufacturing of Nb_3Sn Wires (2/4)

- Most of the processes developed according to the previous scheme relies on the fact that when a bronze/Nb composite is heated up to high temperature (typically: 700 °C), Sn atoms diffuse from the bronze into the Nb and react with Nb atoms to form Nb_3Sn precipitates.

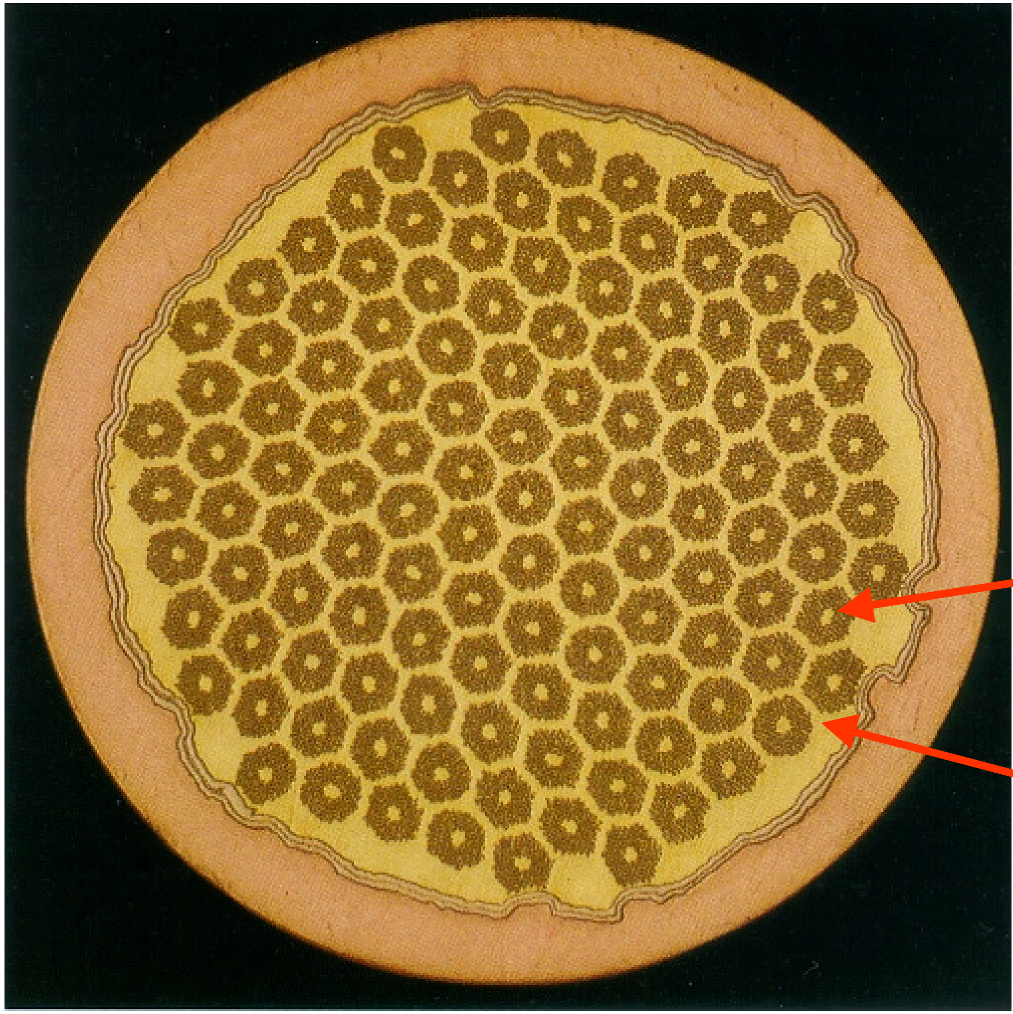
Manufacturing of Nb_3Sn Wires (3/4)

- The diffusion occurs in solid sate and is selective (*i.e.*, only Sn atoms are involved).
- The Nb_3Sn builds up at the bronze/Nb interface and spreads inside the Nb.
- The rate of progression is rather slow and a full reaction of the Nb can require several hundreds of hours.

Manufacturing of Nb_3Sn Wires (4/4)

- At least for processes are used industrially to manufacture Nb_3Sn wires
  - bronze process,
  - internal-tin process,
  - Modified Jelly Roll (MJR) process,
  - Powder in Tube (PIT) process.
- They all call for a high-temperature heat treatment on the final-size wire (or cable or coil).
- The heat-treatment parameters are optimized to achieve full reaction of the precursors while preventing excessive grain growth for optimized pinning.

Example: Bronze process (1/4)



- Bronze-process wires rely on Nb filaments (doped with Ti or Ta) embedded in a bronze matrix.

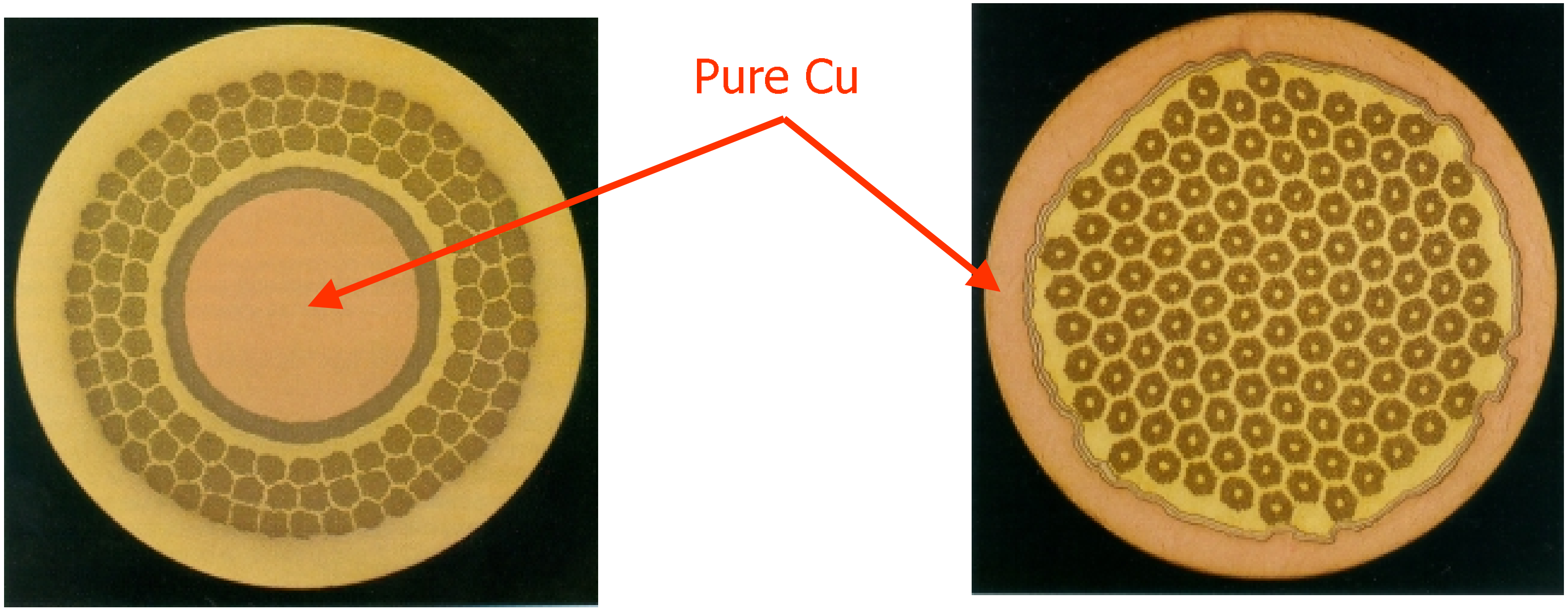
Nb filaments

Bronze matrix

(Courtesy Vacuumschmelze)

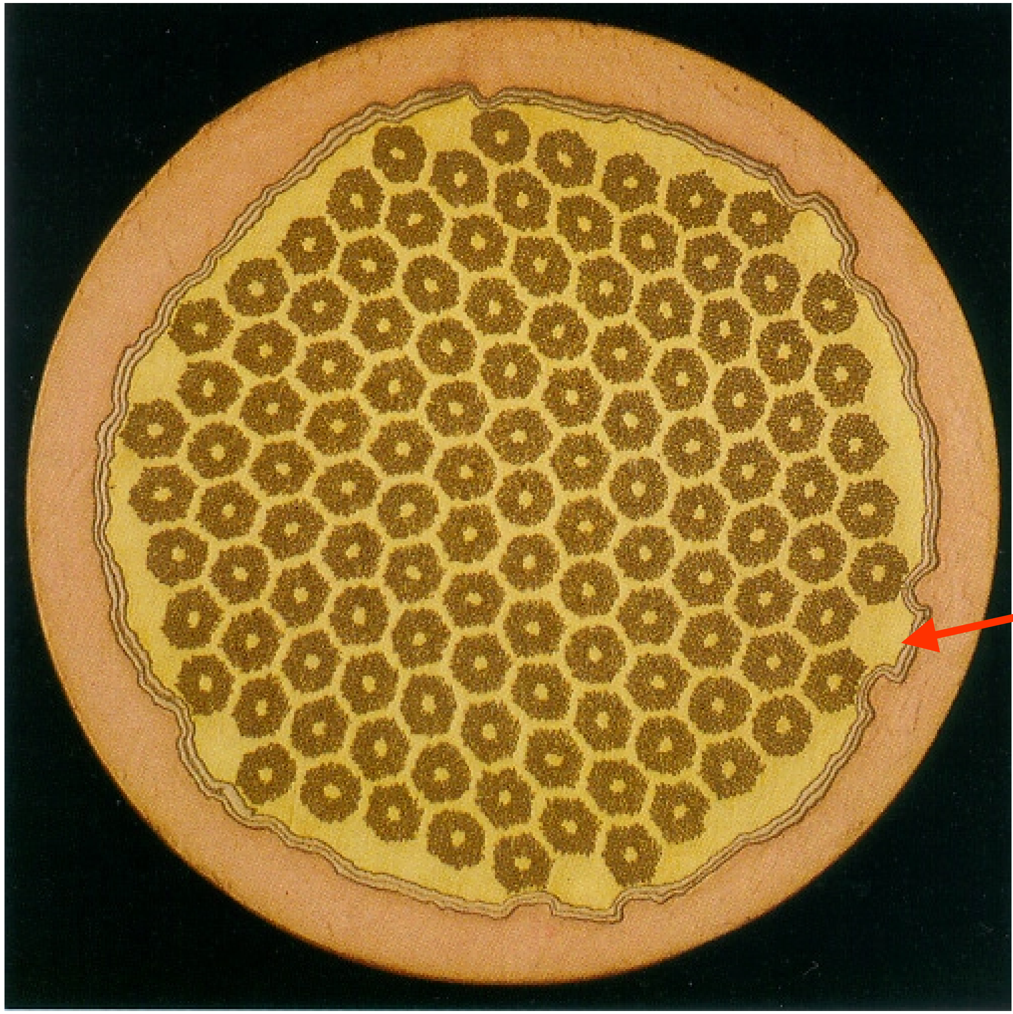
Example: Bronze process (2/4)

- Pure Cu can be added (either internally or externally) to compensate for the high resistivity of bronze and ensure proper stabilization.



(Courtesy Vacuumschmelze)

Example: Bronze process (3/4)

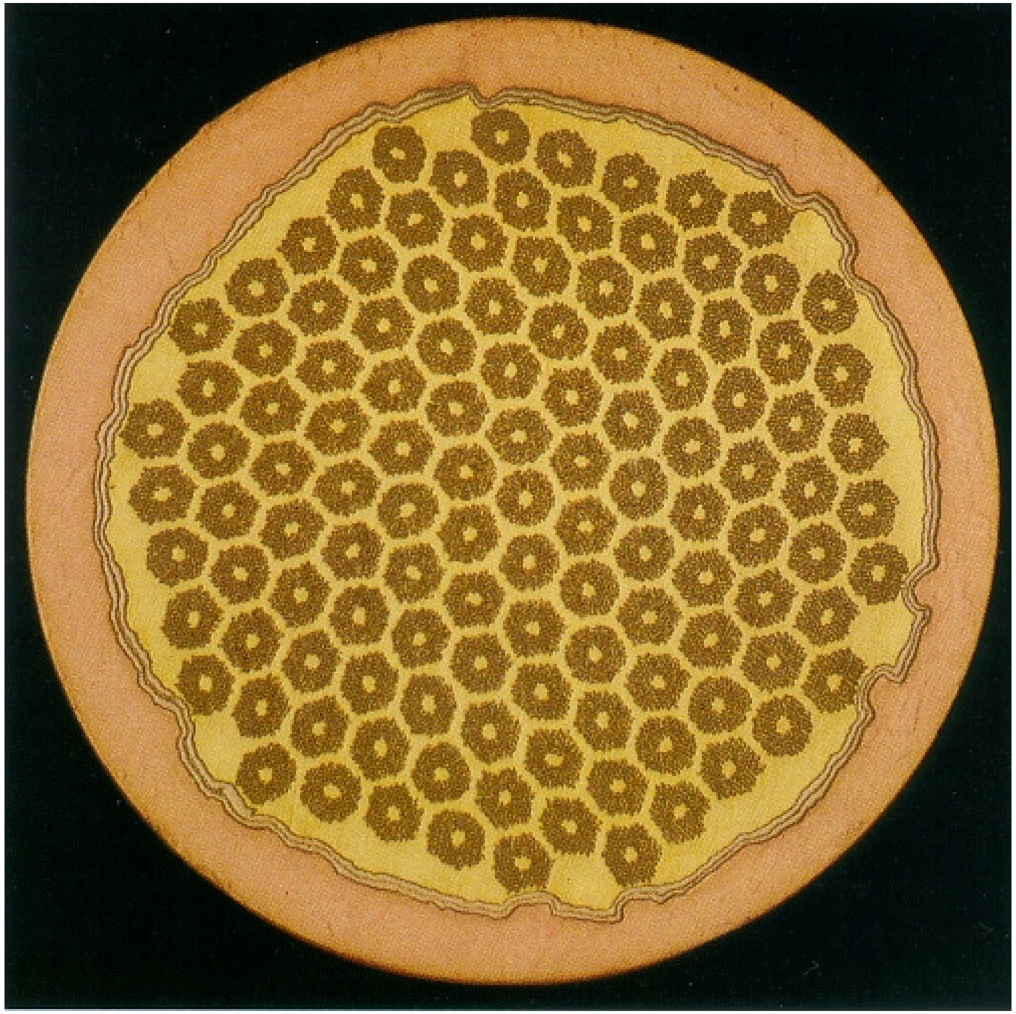


- When pure Cu is added, it must be protected by anti-diffusion barriers to prevent Sn pollution during heat treatment.

Anti-diffusion barriers

(Courtesy Vacuumschmelze)

Example: Bronze process (4/4)



- Typical heat treatment: 40 to 140 h around 700 °C in a vacuum or in inert gas (to prevent, among others, Cu oxidation).

(Courtesy Vacuumschmelze)

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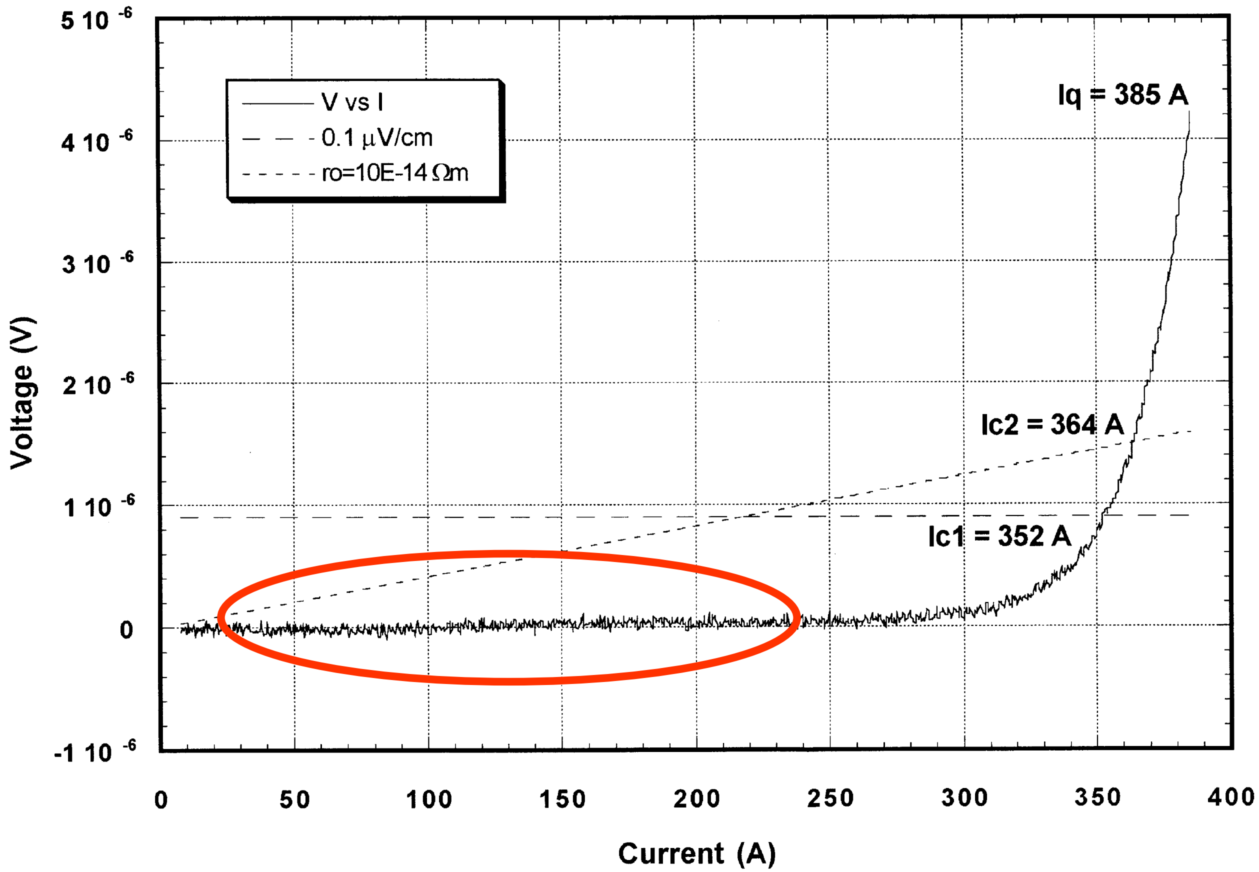
Transition of Multifilamentary Wires

• The transition of a multifilamentary wire from the superconducting state to the normal resistive state is not abrupt but takes place over a certain current range.

• This can be observed by monitoring the voltage-current curve of a wire short sample.

Voltage-Current Curve (1/3)

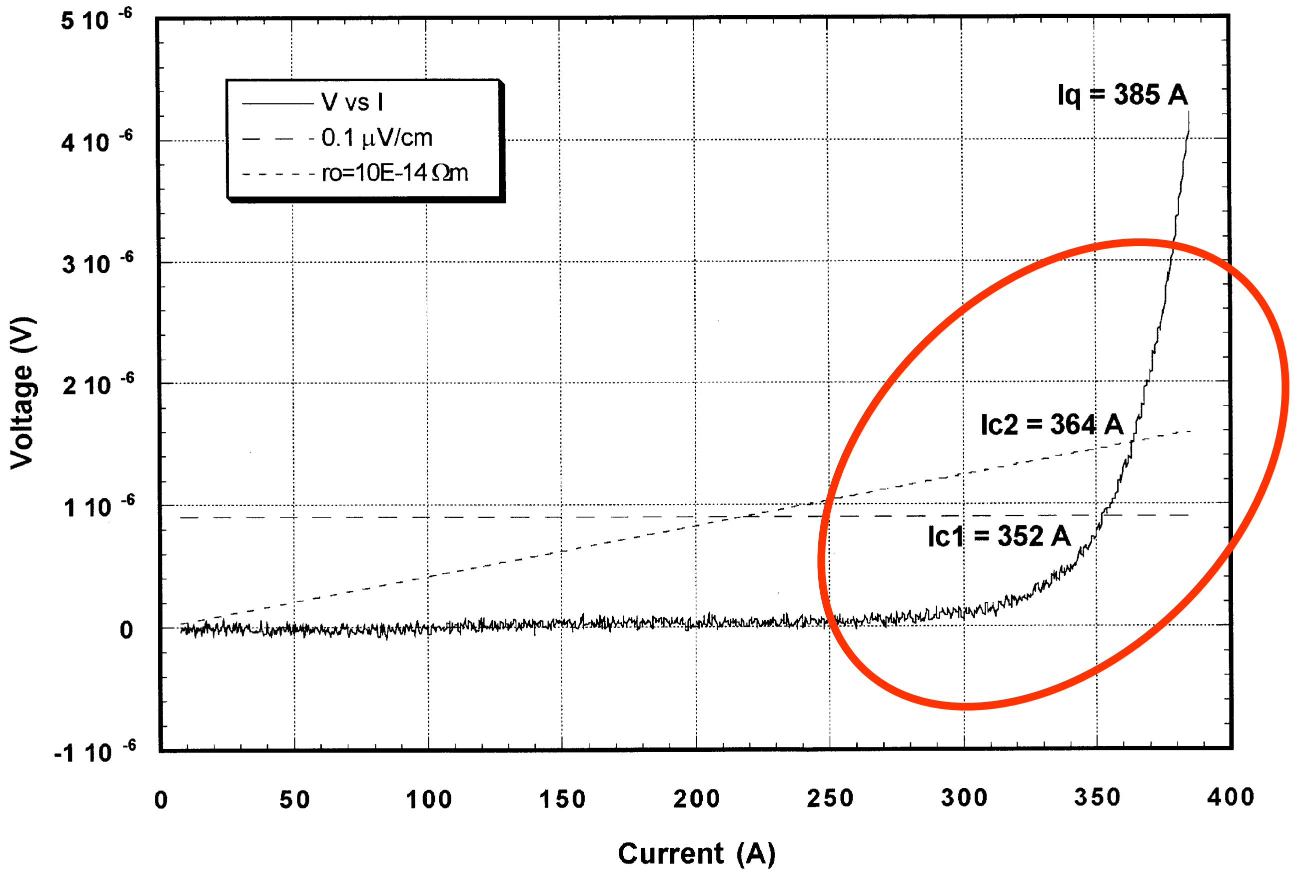
- At low and intermediate transport currents, the voltage, *V*, across the wire short sample is nil and the wire is superconducting.



Nb_3Sn wire at 4.2 K and 7.5 T

Voltage-Current Curve (2/3)

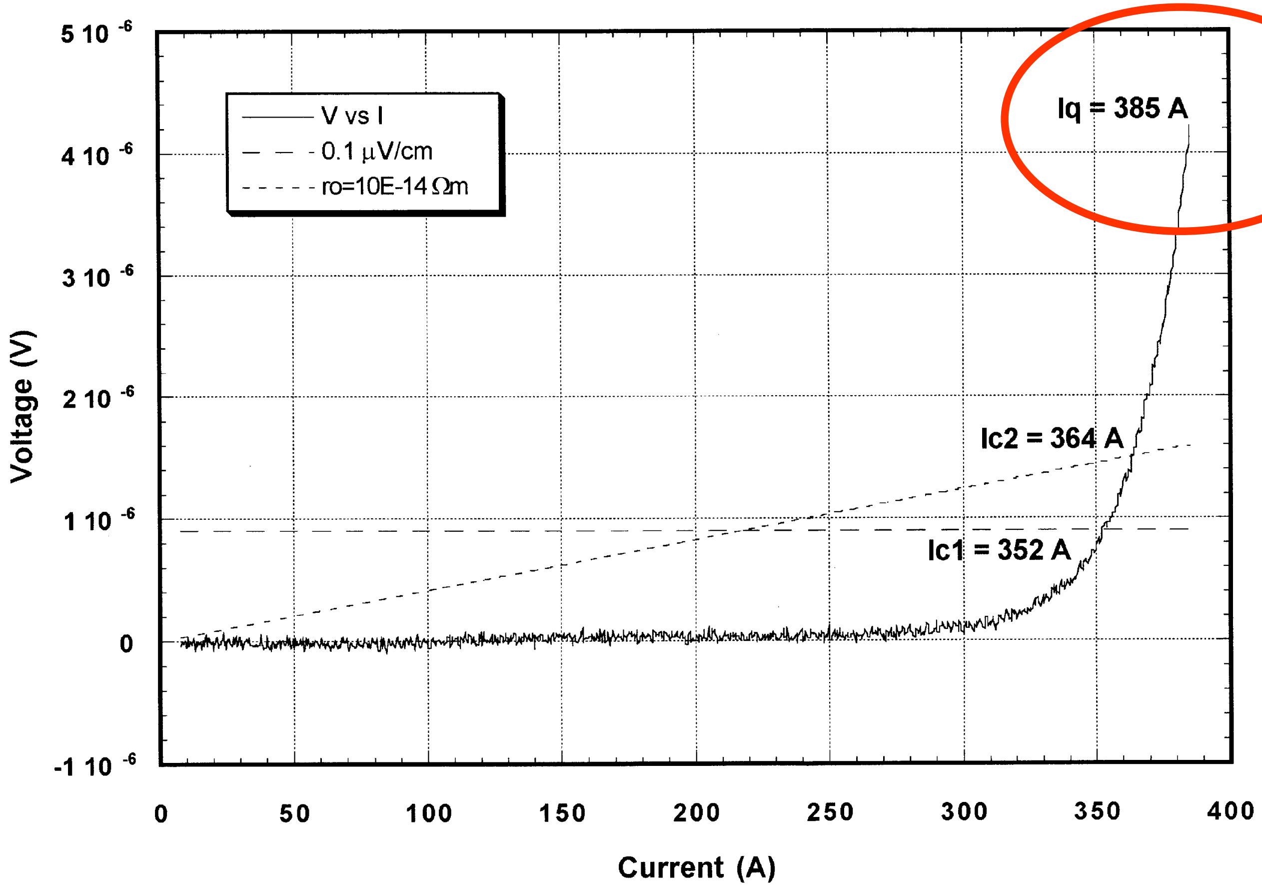
- As the current, I, is increased, there appears a domain where V starts to rise. At the beginning, the rise is reversible, *i.e.*, if I is lowered, V decreases following the same curve as during the up-ramp.



Nb$_3$Sn wire
at 4.2 K
and 7.5 T

Voltage-Current Curve (3/3)

- However, above a certain current, the phenomenon becomes irreversible, and the voltage takes off rapidly and uncontrollably. Such irreversible voltage run-away is the signature of a quench.



Nb_3Sn wire at 4.2 K and 7.5 T

Quench Current

- The current at which the run-away occurs is referred to as the wire short sample *quench current, I_{qss}*.
- The quench current is strongly affected by cooling conditions of wire sample and depends on experimental setup.
- The question then arises of what engineering value to use to characterize the maximum transport-current capability of a wire?

Critical Current

- The engineering value used to characterize the maximum current capability of a superconducting wire is referred to as *critical current, I_C,* and is defined by relying on empirical criterions.

Notations

- Let us consider a wire sample of length, L, and of cross-sectional area, S.
- Let r designate the overall area ratio between the stabilizing copper and the rest, and let V designate the voltage across the sample.
- An apparent electrical field, E_{super}, and an apparent resistivity of superconductor, ρ_{super}, can be defined as

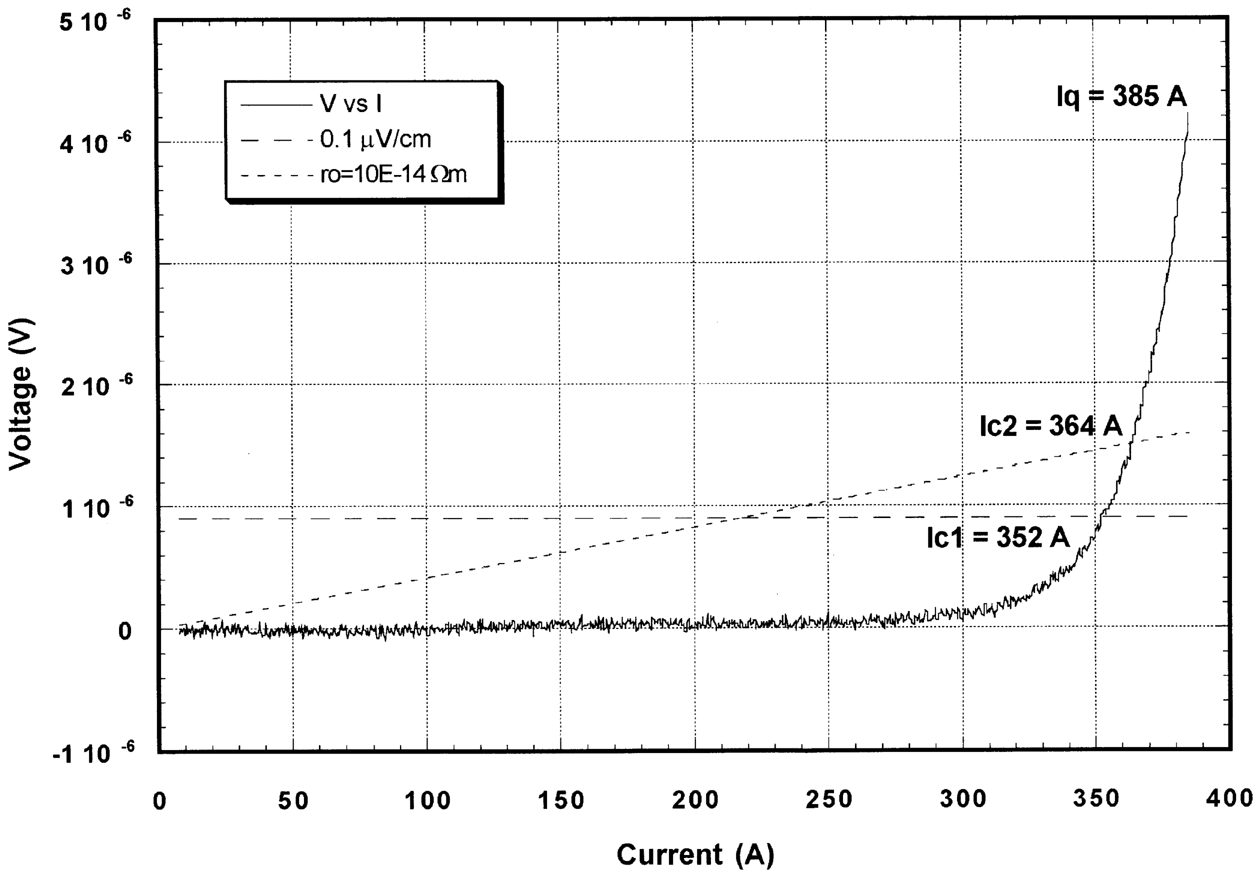
$$E_{\mathrm{super}} = \frac{V}{L} \quad \text{and} \quad \rho_{\mathrm{super}} = \frac{S}{(1+r)L}\frac{V}{I}$$

Critical Current Criterions

- For NbTi and Nb_3Sn wires, the two criterions the most commonly used to determine I_c are
  - – the current value corresponding to an apparent electrical field, E_C, of 0.1 μV/cm,
  - – the current value corresponding to an apparent resistivity of superconductor, ρ_C, of 10^{-14} Ωm.
- On a wire short sample, I_c is usually lower than I_{qss}.

Criterion Comparison

- For the above data we have



I_{qss} = 385 A

I_{C2} (10^{-14} Ωm) = 364 A

I_{C1} (0.1 μV/m) = 352 A

Critical Current Density

- The critical current determined by either of the aforementioned criterions can be translated into an average critical current density in non-copper, J_C, using

$$I_C = J_C \frac{S}{1+r}$$

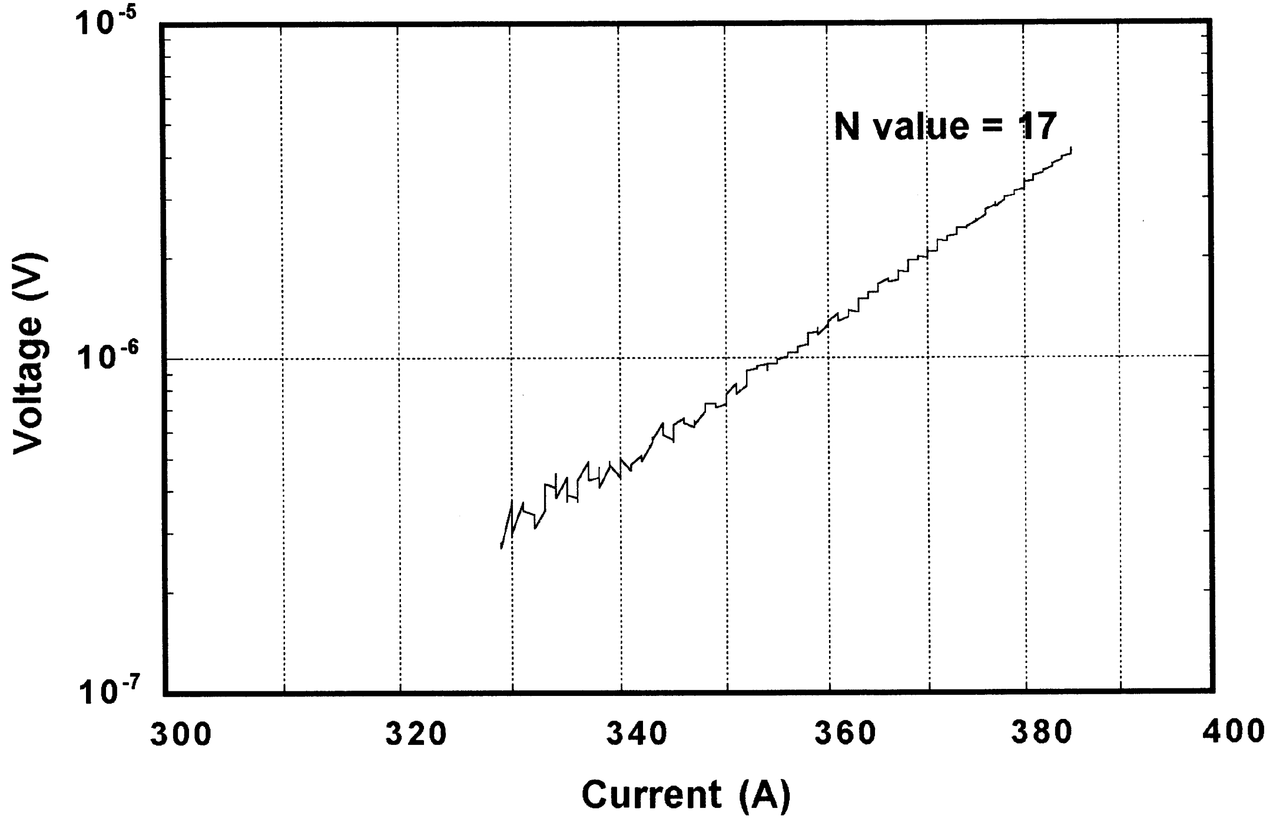
- I_C and J_C both depend on T and B.

Curvature of *V–I* Characteristic

- To fully characterize the wire, it is also interesting to quantify the sharpness of the transition from the superconducting to the normal resistive state.
- This can be done by plotting $\ln(V)$ [or $\ln(\rho)$], as a function of $\ln(I)$.

ln *V* versus ln *I* Curve

- It appears that ln(*V*) [and similarly, ln(ρ)] increases quasi-linearly as a function ln(*I*) over a broad range (typically from E_C to $10E_C$ or ρ_C to $10\rho_C$).



Nb_3Sn wire
at 4.2 K
and 7.5 T

Resistive Transition Index (1/2)

- The onset of the resistive transition can be fitted by simple power laws of the form

$$\frac{V}{V_C} = \left(\frac{I}{I_C}\right)^N \quad \text{and} \quad \frac{\rho_{\text{super}}}{\rho_C} = \left(\frac{I}{I_C}\right)^{N-1}$$

where V_C is the voltage across the wire sample corresponding to E_C

$$V_C = E_C\, L$$

Resistive Transition Index (2/2)

- The parameter *N* is referred to as *resistive transition index* or more simply *N-value.*
- It is representative of the curvature of the *V-I* characteristics: the larger *N*, the sharper the transition.
- The *N*-value, like I_C, depends on temperature and field.
- High-performance wires have *N*-values in the 30 to 50 range.

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Superconductor Magnetization (1/2)

- Bulk type-II superconductors react to shield their inner core from any change in amplitude or orientation of applied field.
- The shielding is realized by induction of magnetization currents at the superconductor periphery.
- The magnetization currents distribute themselves so as to produce, within the superconductor, a magnetic field exactly opposite to the change in applied field.

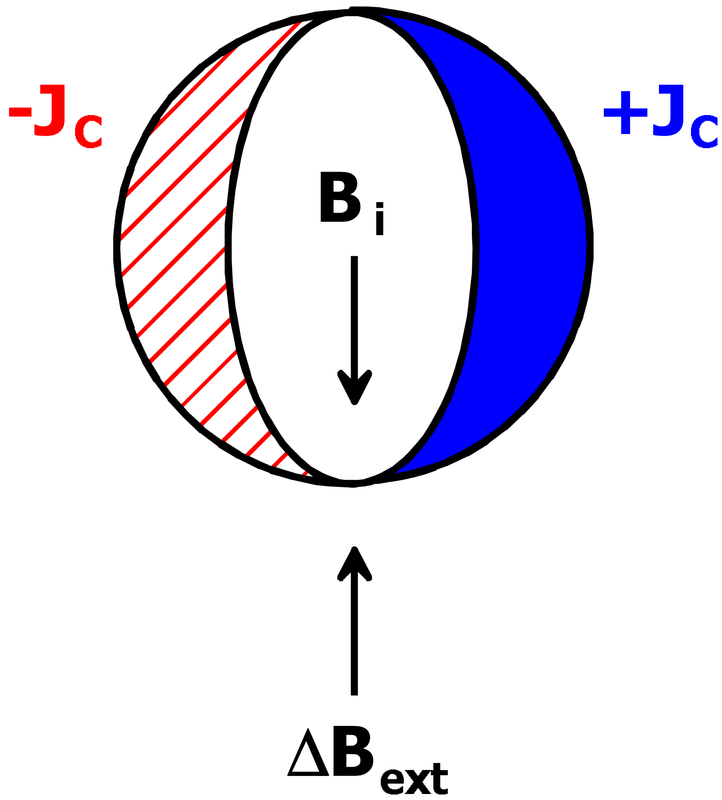
Superconductor Magnetization (2/2)

- Unlike regular eddy currents, the superconductor magnetization currents are proportional to the amplitude of applied field change (and not to the rate of variation), and they do not decay once the applied field is held constant.
- They are usually referred to as *persistent magnetization currents.*

Critical State Model

- In the so-called *critical state model,* first proposed by C.P. Bean in 1962, the density of the persistent magnetization currents is assumed to be the superconductor critical current density.
- This model is well suited to interpret most observed behaviors.

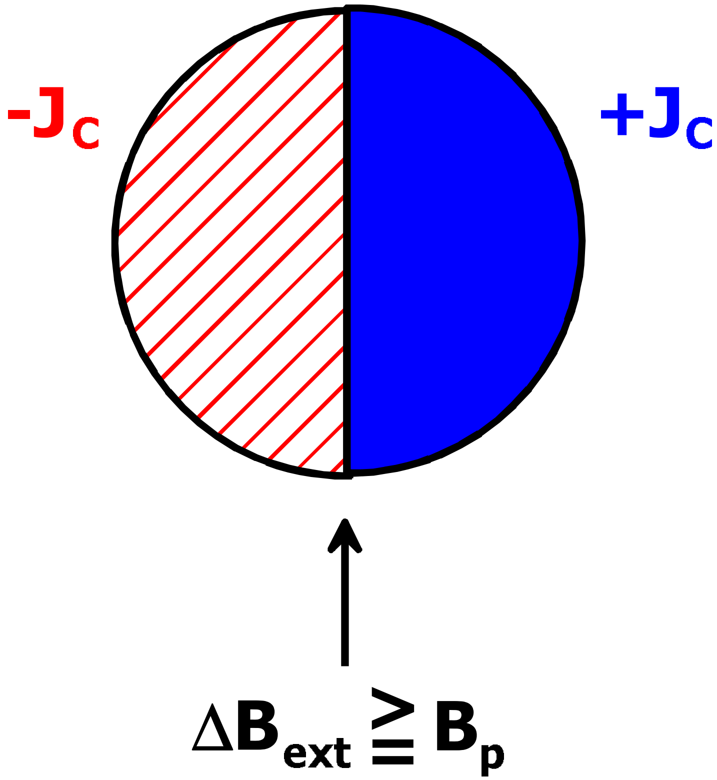
Filament Magnetization (1/4)



- In the case of a filament, the distribution of persistent magnetization currents assumes the shape of an elliptical shell.
- The shell parameters are such that

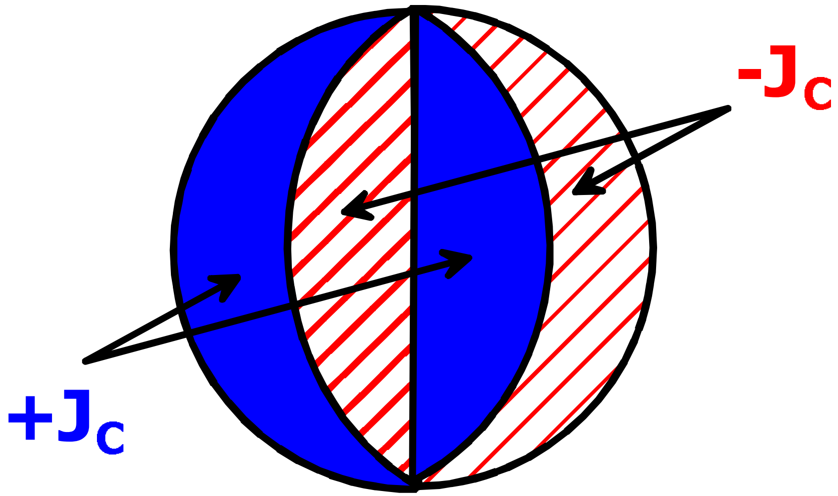
$$B_i = -\Delta B_{ext}$$

Filament Magnetization (2/4)



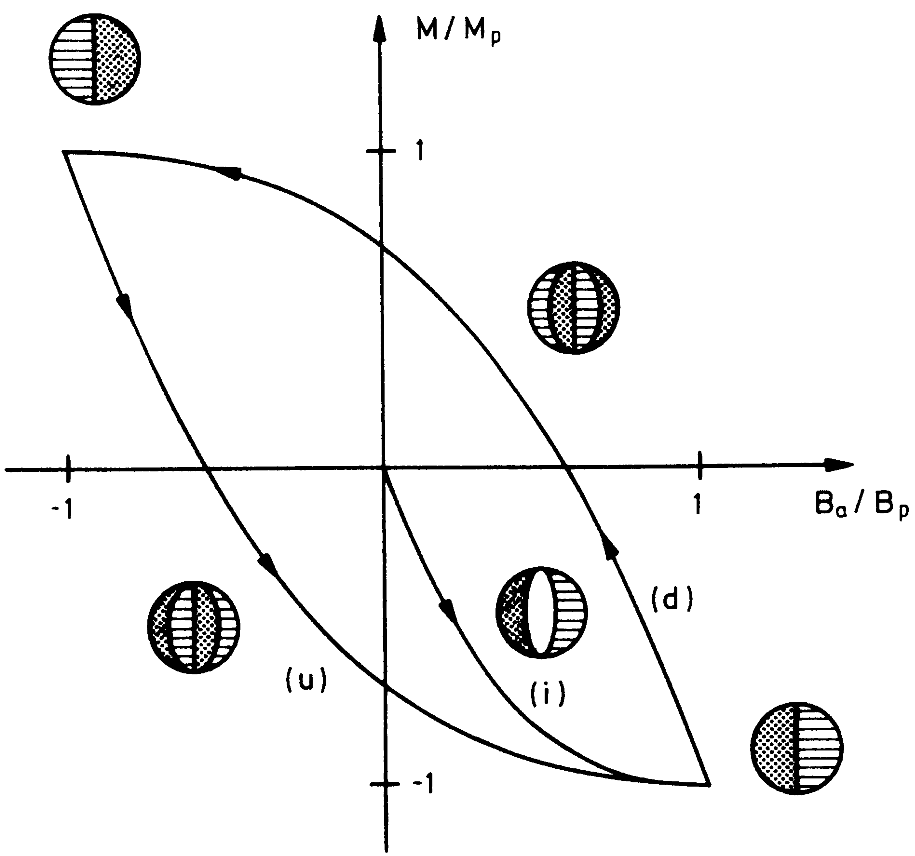
- As the applied field is increased, the ellipse eccentricity decreases, until the magnetization currents fill up the whole filament.
- The field at which this occurs is called the penetration field, B_p.

Filament Magnetization (3/4)



- Then, if the field is decreased, a new shell is created at the filament periphery, with currents flowing in opposite directions.
- And so on.

Filament Magnetization (4/4)



- As a result, a superconducting filament subjected to a field cycle gets magnetized and its magnetization exhibits an hysteresis.
- The magnetization amplitude can be shown to be directly proportional to filament diameter.

(Courtesy P. Schmüser)

NbTi Wire Magnetization (1/2)

- For most NbTi wires, the observed wire magnetization is consistent with what can be expected from the properties of the filaments taken individually.
- In particular, it is directly proportional to filament diameter.

NbTi Wire Magnetization (2/2)

- The effects of NbTi wire magnetization can be limited by reducing filament diameter.
- However, reducing filament diameter means additional drawing steps, and even possibly another billet re-stacking, which increases processing costs.
- SSC, RHIC and LHC magnets rely on wires with filament diameter of the order of 5 μm.

Nb_3Sn Wire Magnetization (1/3)

- For most Nb_3Sn wires (especially those produced by internal-tin and MJR processes), the observed wire magnetization is usually greater than what can be expected from initial wire layout.
- This indicates that the reacted filaments are more or less coupled and react collectively to applied field changes.
- The origin of this collective behavior is not yet understood, and could result from interfilament bridging induced during the solid-state diffusion process.

Nb_3Sn Wire Magnetization (2/3)

- The observed behavior is usually characterized by an effective filament diameter determined from the amplitude of the measured magnetization.
- For high-J_C wires with small initial filament diameters (1 to 5 μm?), the effective filament diameter can exceed 100 μm at 12 T, and the wire can exhibit flux jumps at low fields.

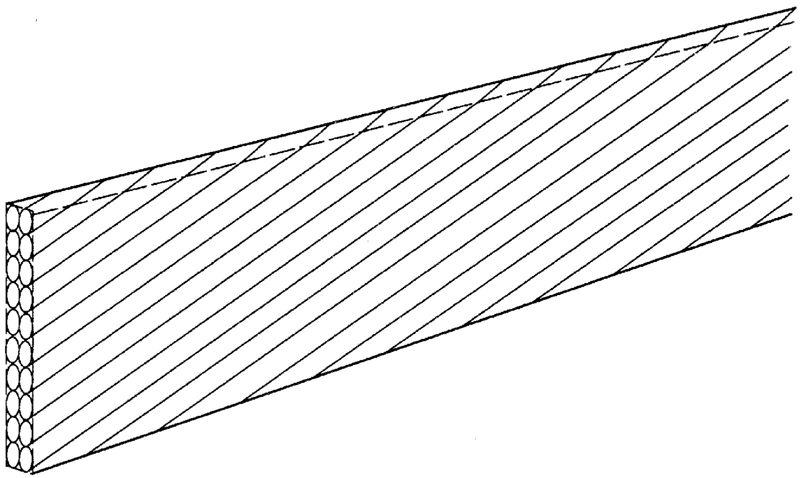
Nb_3Sn Wire Magnetization (3/3)

- The effective filament diameter may be reduced by increasing interfilament spacing and/or by implementing additional barriers to isolate filament bundles of small diameters.
- However, this may degrade the overall critical current density in the non-copper and will increase processing costs.
- Several R&D programs are being carried at various wire manufacturers around the world to address this issue (*e.g.,* IGC and OST in the USA, MELCO in Japan, and Alstom/MSA in France).

Contents

Rutherford-Type Cable

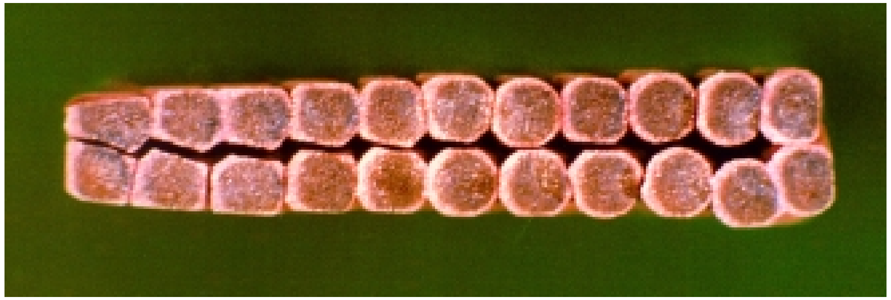
- Accelerator magnet coils usually rely on Rutherford-type cables, made up of a few tens of strands, twisted together, and shaped into a flat, two-layer cable.



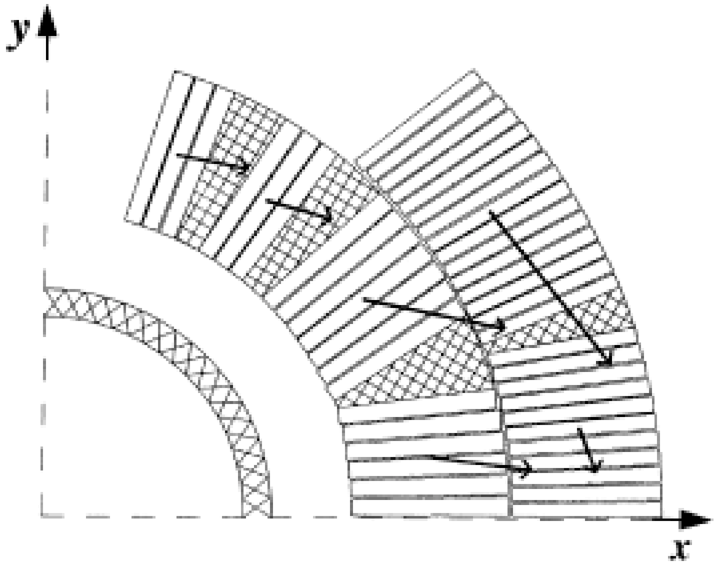
Rutherford-Type Cable
(Courtesy T. Ogitsu)

Cable Keystone

- For cosθ-type coils, the Rutherford-type cables are given a slight *keystone* to assume an arch-shape upon stacking.



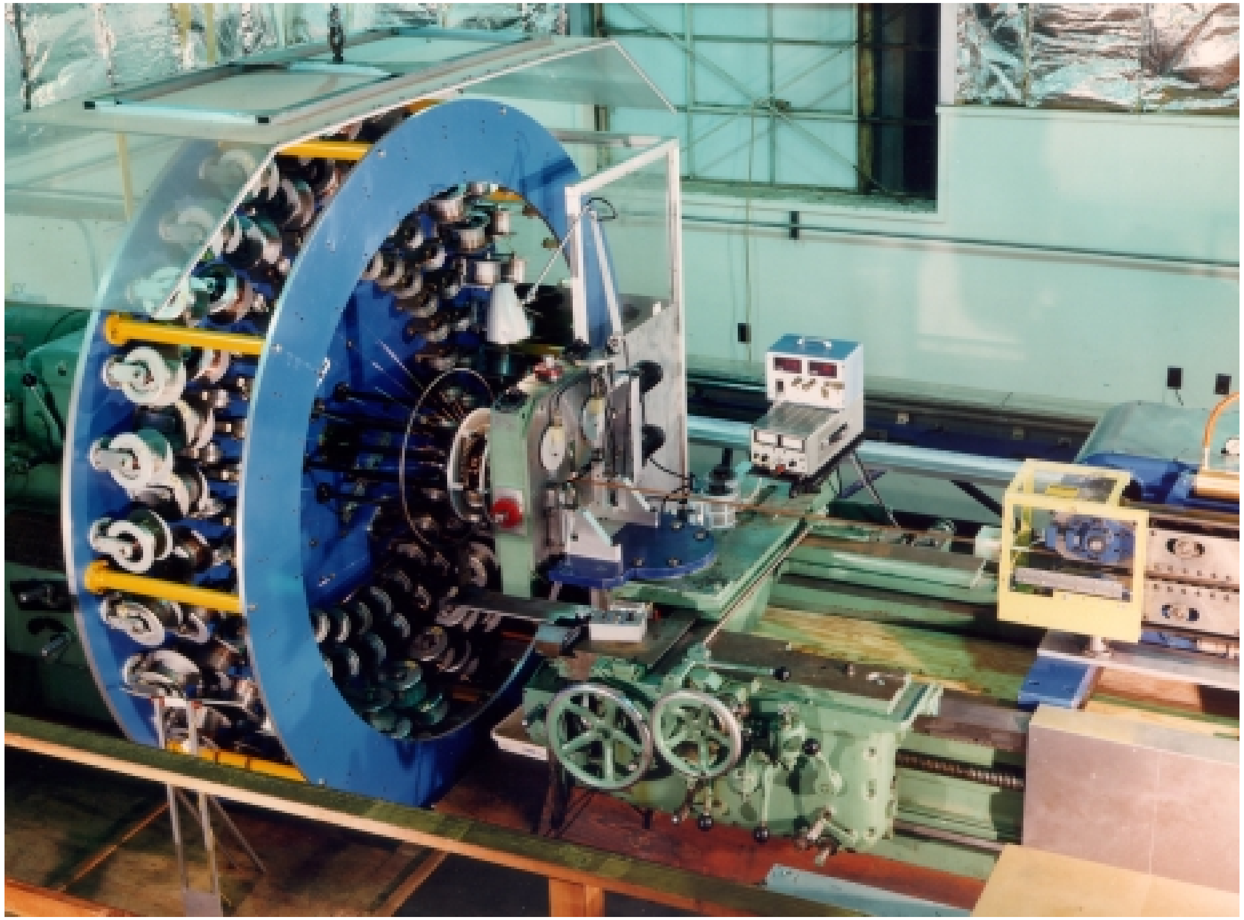
NbTi Cable with a 4.7° Keystone (Courtesy A. Yamamoto)



Conductor Distribution in a Dipole Coil Assembly Quadrant (Courtesy R. Gupta)

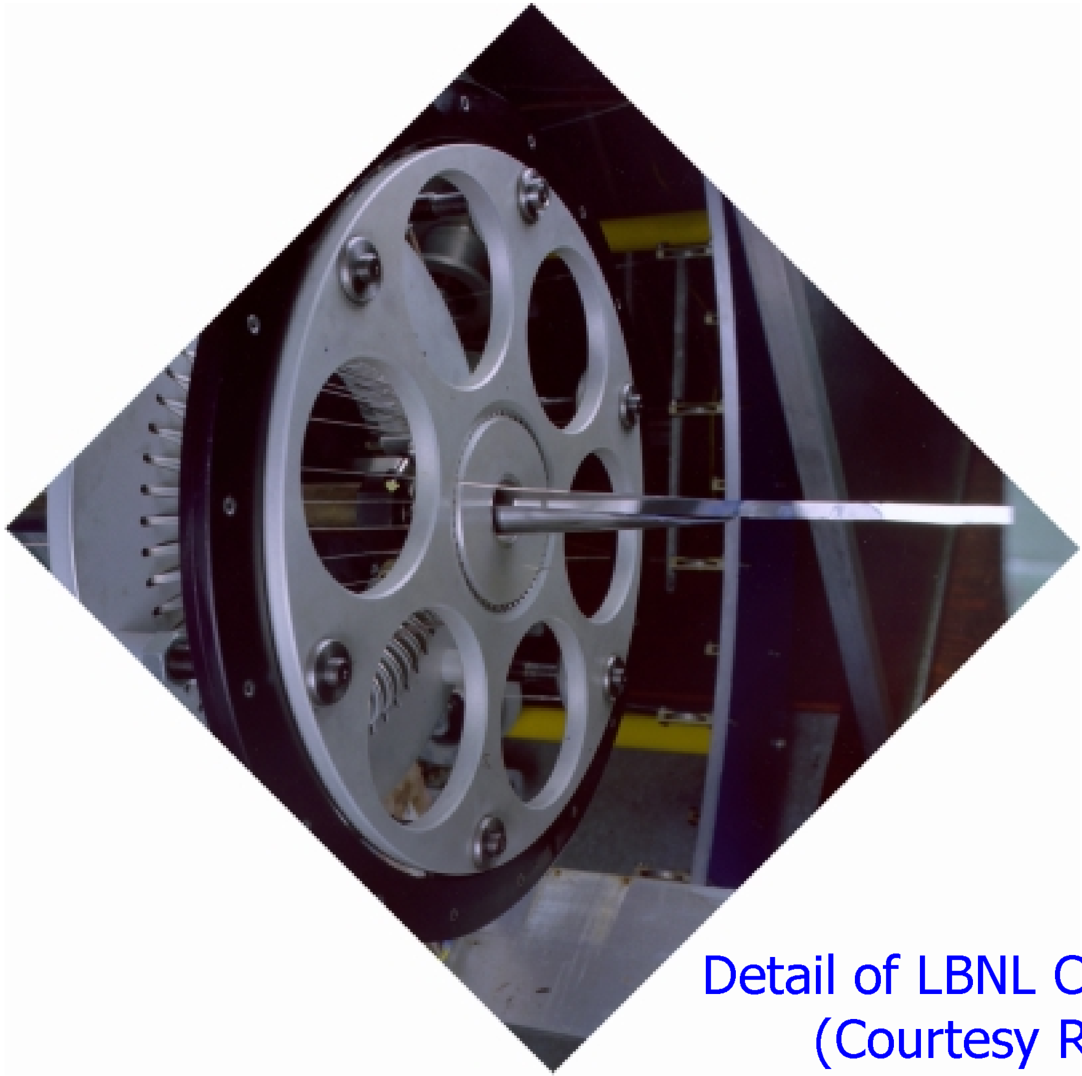
Cabling Machine (1/3)

- Rutherford-type cabling machines include a rotating drum to support strand spools and are driven by a caterpillar-type belt.



LBNL Cabling Machine
(Courtesy R. Scanlan)

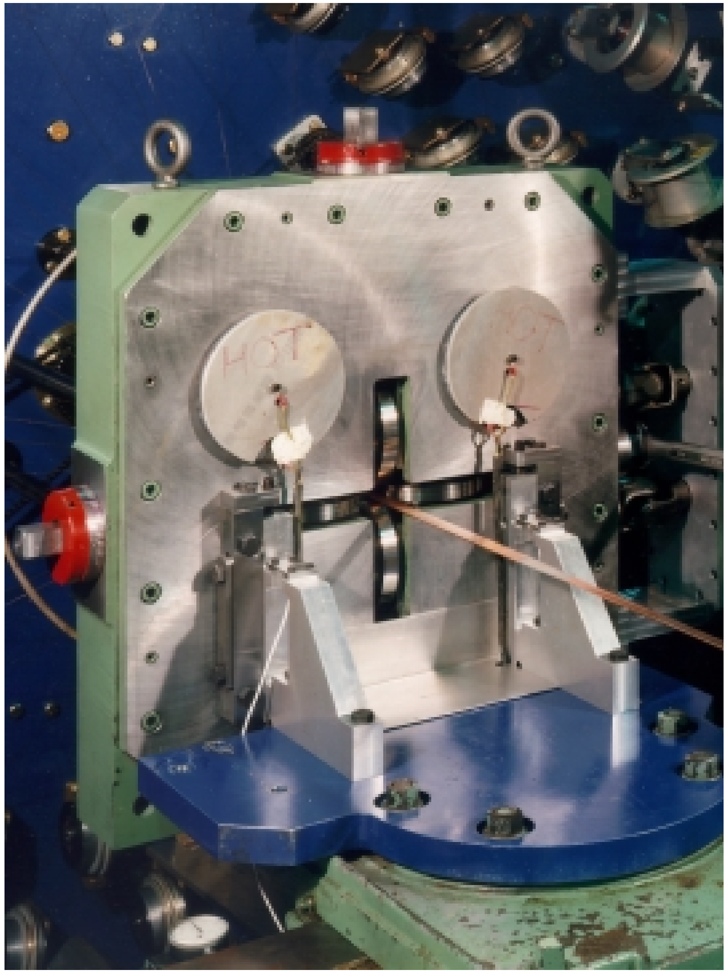
Cabling Machine (2/3)



- The strands are twisted together around a cabling mandrel shaped like a screwdriver blade.

Detail of LBNL Cabling Machine
(Courtesy R. Scanlan)

Cabling Machine (3/3)



Detail of LBNL Cabling Machine
(Courtesy R. Scanlan)

- As the cable leaves the cabling mandrel, it enters a Turk's-head roller die, which consists of four roller dies arranged at given angles to form a trapezoidal orifice.
- The Turk's-head die squeezes the cable into its final configuration.

Cable Design and Manufacturing Issues

- The main issues regarding Rutherford-type cable design and manufacturing are
  - compaction,
  - control of outer dimensions,
  - limitation of critical current degradation,
  - control of inter-strand resistances.

Cable Compaction

- The cable compaction should be
  - neither too small, to leave enough void (typically of the order of 10% in volume) for liquid helium cooling,
  - nor too large, to ensure good mechanical stability and high overall current density.

Cable Dimensions

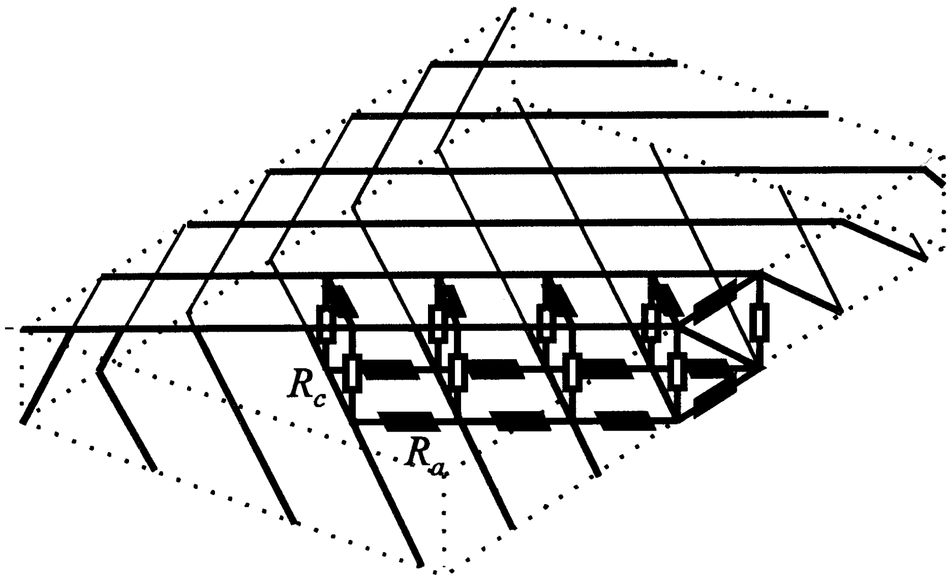
- The cable outer dimensions must be kept within very tight tolerances.
- They are controlled on-line by a so-called Cable Measuring Machine (CMM).

Cabling Degradation

- The critical current of a strand extracted from a cable is usually lower than that of a virgin strand.
- This cabling degradation is attributed to filament deformations (NbTi and Nb_3Sn wires) and anti-diffusion barrier breakages (Nb_3Sn wires) in the areas where the strand is bent in a hairpin-like manner at the cable edges.
- The amount of copper and the way it is distributed between the strand core and its periphery have been shown to influence cabling degradation.

Interstrand Resistances (1/2)

- There are two types of interstrand resistances



(Courtesy A. Verweij)

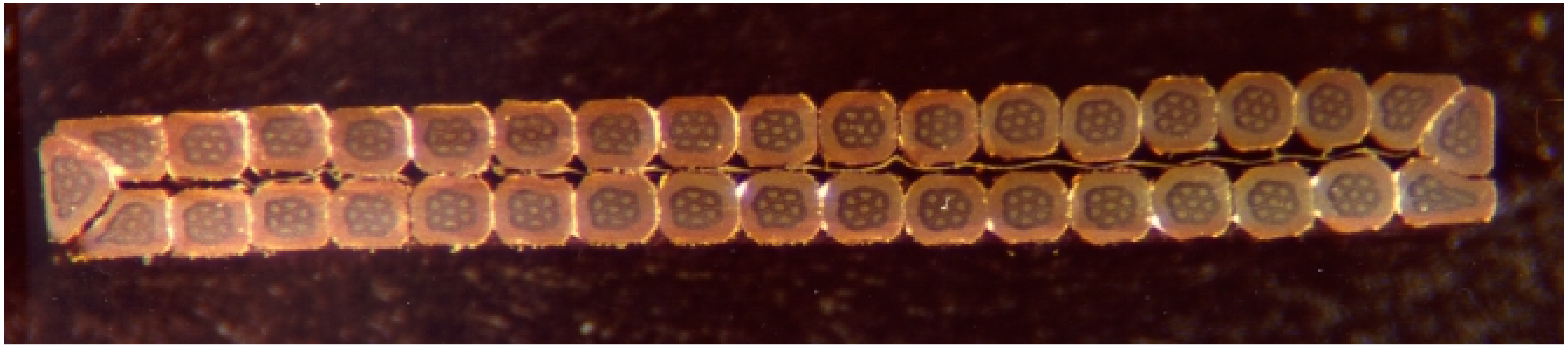
– crossover resistances, R_C, localized at the crossings between strands of the two layers,
– adjacent resistances, R_a, distributed between adjacent strands of a same layer.

Interstrand Resistances (2/2)

- The interstrand resistances should be
  - neither too small, to limit field distortions induced by inter-strand coupling currents while ramping,
  - nor too large, to allow current redistribution among cable strands.
- This imposes a lower limit on R_c, where large interstrand coupling currents can circulate, and an upper limit on R_a, which is believed by most authors (*e.g.*, M.N. Wilson) to dominate interstrand current distribution.
- In practice, the main issue is to control R_c.

Cored Cable

- One way of controlling R_C is to introduce a thin insulating core between the two strand layers.
- The core can be made up of stainless steel, titanium or insulating material.



Nb_3Sn Cable Developed by Alstom/MSA for CEA/Saclay
With a 25-µm-Thick Stainless-Steel Core

Contents

- Review of Superconducting Materials
- Superconducting Multifilamentary Composites
- Transition of Multifilamentary Wires
- Magnetization of Multifilamentary Wires
- Rutherford-Type Cables
- **Super-stabilized Conductors**
- Conductor Insulation

Super-Stabilized Conductor

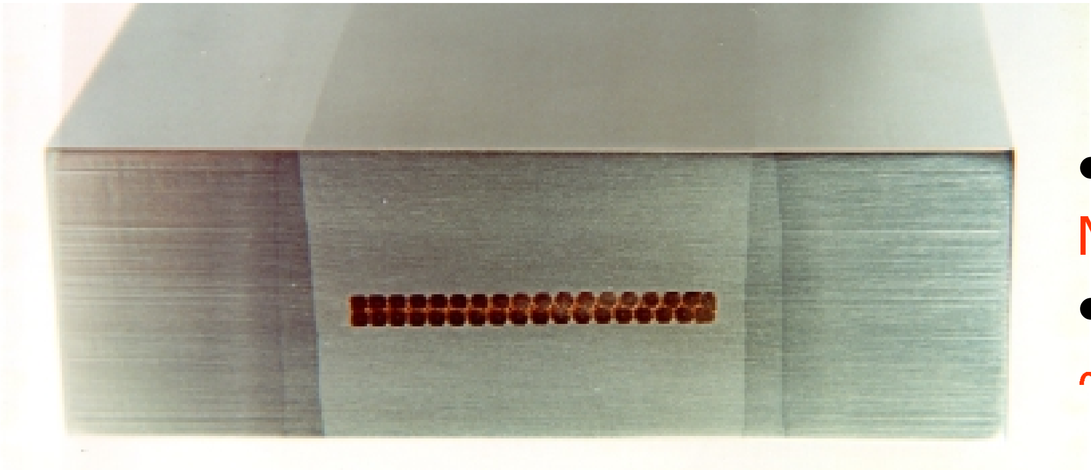
- For large-inductance magnets with a long time constant of current discharge, the normal metal stabilizer included in the cable strands may not be sufficient to prevent excessive heating in the case of a quench.
- The strand stabilization can be completed by adding a large volume of low-resistivity, normal metal around the cable itself.
- Such addition is referred as super-stabilization.

Super-Stabilized Conductor for Detector Magnet

- The main application of super-stabilized conductors are the large magnet systems for high-energy-physics experiments.
- In these systems, the structure must be as transparent as possible to the studied particles, and the super-stabilizer is chosen to be high purity aluminum.

Example: CMS Conductor (1/2)

- The super-stabilizer is implemented by co-extrusion of a Rutherford-type cable with paste-like aluminum at ~400 °C.



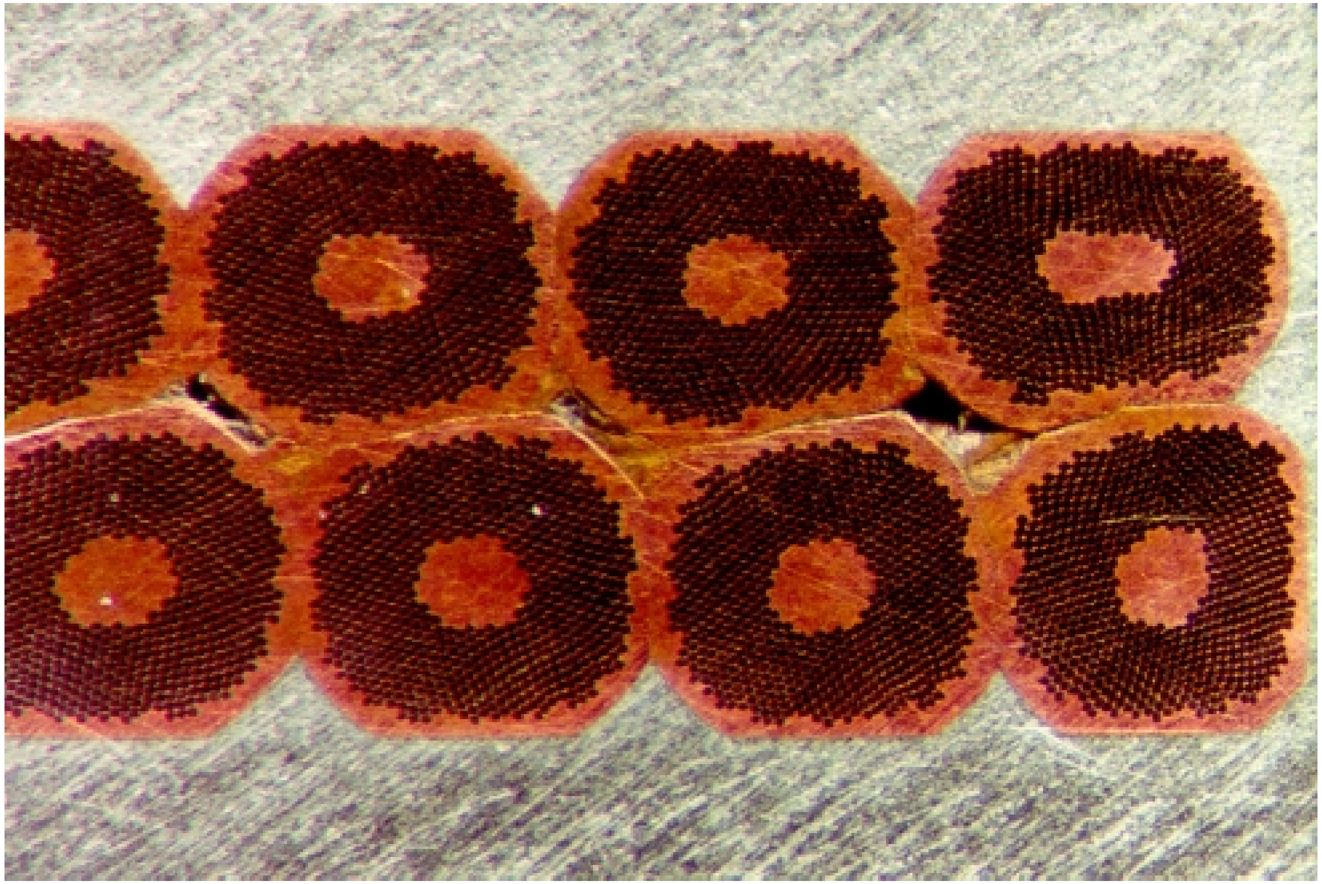
CMS Conductor

- The CMS cable counts 32 NbTi strands.
- The critical current is ~50,000 A at 4.2 K and 5 T.

- In the case of CMS, an aluminum alloy reinforcement is electron-beam welded on both sides of the conductor.

CMS Conductor (2/2)

- The contact between cable strands and super-stabilizer must be optimized to limit electrical resistance.



Close-Up View of CMS Conductor

Contents

Insulation Requirements (1/2)

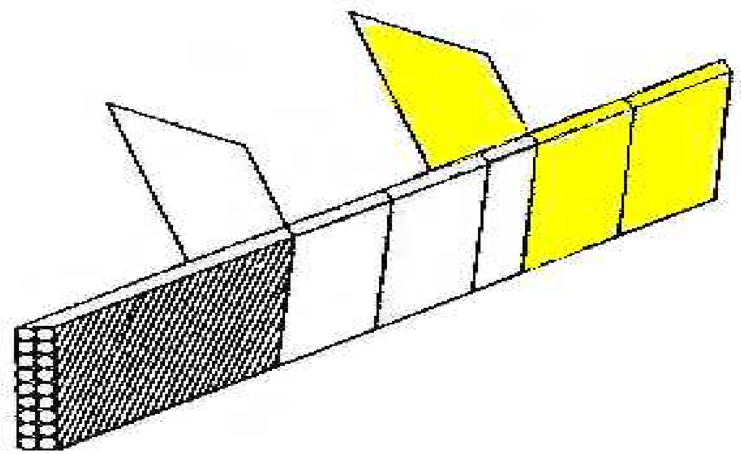
- The main requirements for cable insulation are
  - – good dielectric strength in helium environment and under high transverse pressure (up to 150 MPa?),
  - – small thickness to maximize overall current density in magnet coil and good physical uniformity to ensure proper conductor positioning,
  - – retention of mechanical properties over wide temperature range (in particular, down to liquid helium temperature),
  - – ability to withstand radiations in accelerator environment.

Insulation Requirements (2/2)

- In addition, the insulation system is required to provide a mean of bonding coil turns together to give the coil a semi-rigid shape and facilitate its manipulation during subsequent steps of magnet assemby.
- It is also desirable that the insulation be somewhat porous to helium for better conductor cooling.

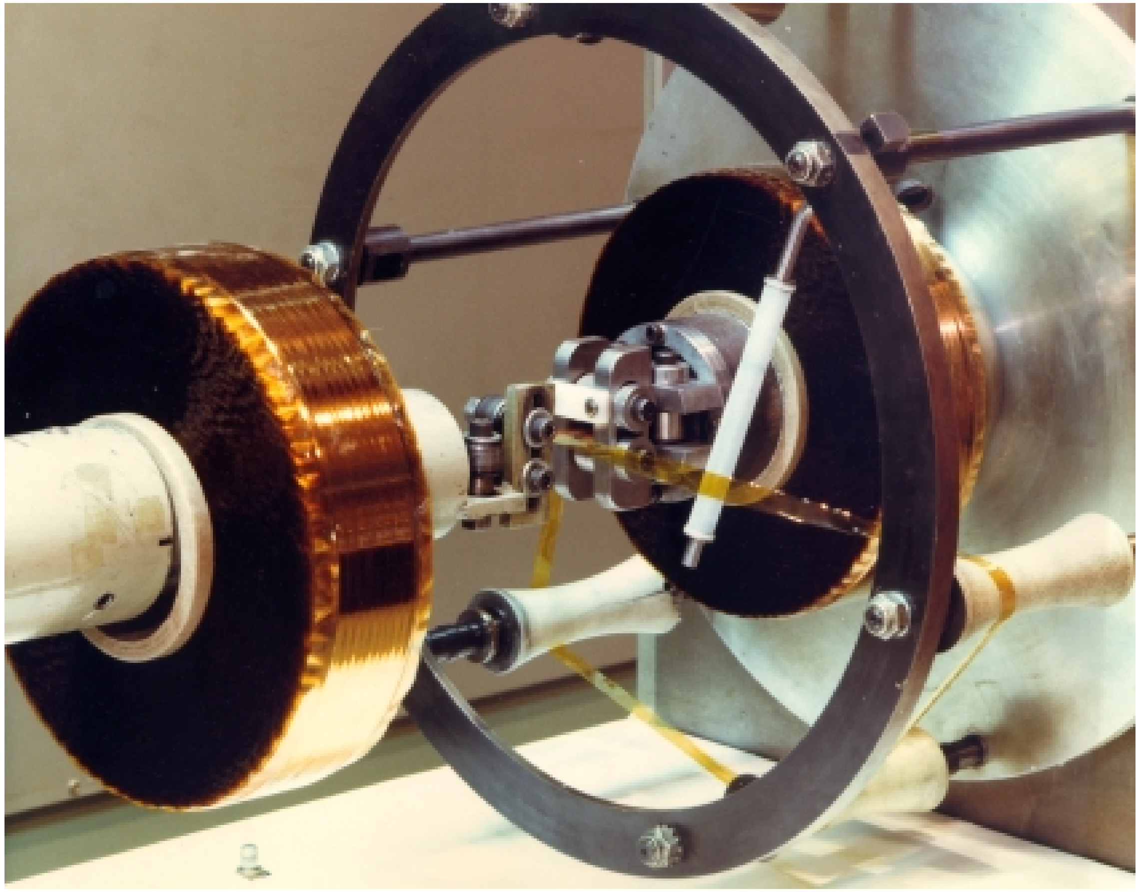
Insulation of NbTi cables (1/3)

- NbTi cables are usually wrapped with several layers of polyimide tapes, such as Kapton®.



- The outer tape is coated with a polyimide-adhesive on its outer surface, which soften when heated to temperatures in the 150-to-200 °C range.

Insulation of NbTi cables (2/3)



- The tapes are wrapped around the cable prior to winding.

Insulation of NbTi cables (3/3)

- Upon winding completion, the coils are transferred into a mold of very accurate dimensions and cured into a rigid shape.
- The curing operation is instrumental in determining coil geometry.

Insulation of Nb_3Sn cables (1/5)

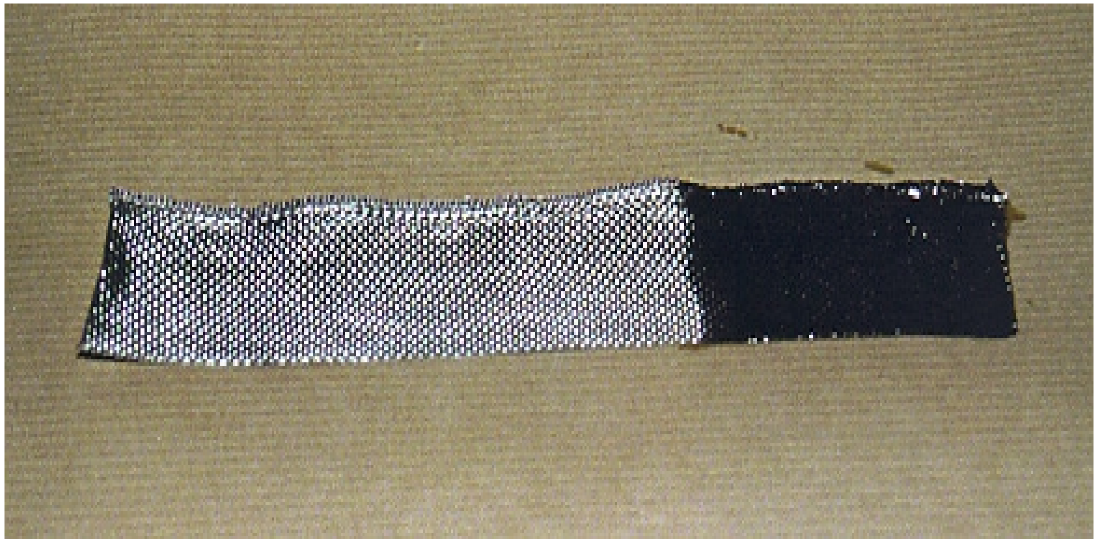
- The insulation of Nb_3Sn cables depend on the timing of the heat treatment needed for Nb_3Sn compound formation.
- If the heat treatment is performed prior to winding ("react and wind" process), the insulation can be the same as for NbTi cables.

Insulation of Nb_3Sn cables (2/5)

- If the heat treatment is performed upon winding completion ("wind and react" process), the insulation is applied in two steps
  - wrapping of cable with a mineral fiber tape or sleeve prior to winding and heat treatment,
  - vacuum-impregnation of coil with epoxy resin after heat treatment.
- In the latter scheme, the mineral fibers used for the tape or sleeve must be able to sustain the heat treatment without significant degradation (*e.g.*, R ou S2 glass, quartz or ceramic fibers).

Insulation of Nb_3Sn cables (3/5)

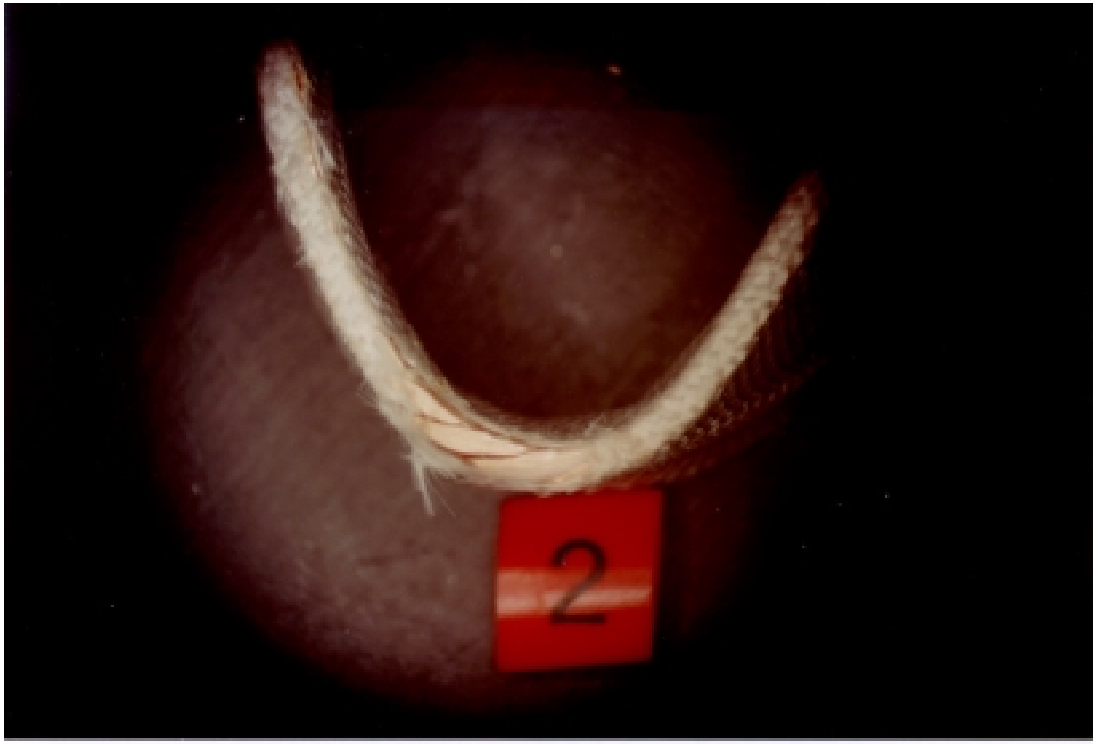
- In addition, all organic materials, such as sizing or finish, must be removed from the fibers prior to heat treatment, to prevent the formation of carbon residues that may degrade dielectric strength.



- Example of a glass fiber tape that was heat-treated without removing sizing.
- The carbon residues were revealed by dipping the tape into resin.

Insulation of Nb_3Sn cables (4/5)

- The sizing removal is usually performed by carbonization in air prior to conductor insulation, but de-sized tapes or sleeves become fragile and easy to tear off by friction.



- Bending test on a Nb_3Sn cable wrapped with a de-sized quartz fiber tape.

Insulation of Nb_3Sn cables (5/5)

- Cable insulation is one of the most difficult issues in the manufacturing of Nb_3Sn magnets, especially by the "wind and react" technique.
- It is an area where innovative solutions are definitely needed to improve feasibility and reduce production costs.